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EVALUATION OF SF6 AS A TRACER GAS FOR DETERMINING SMOKE 1/1

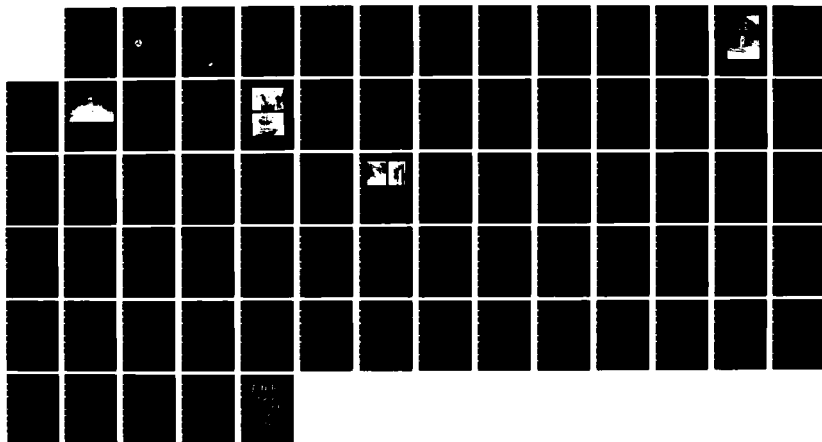
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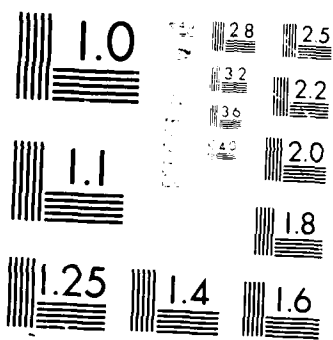
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EVALUATION OF SF<sub>6</sub> AS A TRACER GAS FOR DETERMINING  
SMOKE MOVEMENT IN SHIPBOARD FIRES

DAVID E. BEENE, JR.  
AND  
HARRY E. SCHULTZ, III

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U.S. COAST GUARD RESEARCH AND DEVELOPMENT CENTER  
AVERY POINT, GROTON, CONNECTICUT 06340-6096



FINAL REPORT  
AUGUST 1986

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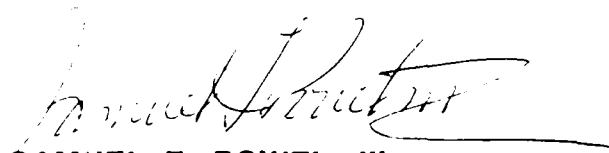
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15. Supplementary Notes					
16. Abstract  This test program evaluated the application of using SF <sub>6</sub> as a tracer gas for determining smoke movement in ships. The testing was carried out on board the U.S. Coast Guard research vessel ALBERT E. WATTS. The test area consisted of a pressurized test citadel containing three deck levels with compartments and passageways. The movement of SF <sub>6</sub> was recorded and evaluated in three test phases. These included: (1) a passive or natural release of SF <sub>6</sub> into the test compartment, (2) a dynamic or fan forced release of SF <sub>6</sub> into the test compartment, and (3) SF <sub>6</sub> being released into a fire in the test compartment. Two technical methods, a continuous reading analyzer and a chromatographic analysis of grab samples, were used to monitor for the presence of SF <sub>6</sub> .  The test results indicate that SF <sub>6</sub> can be used to provide a qualitative picture of smoke movement sufficient to evaluate ventilation systems and shipboard smoke control procedures. The SF <sub>6</sub> behavior simulated smoke movement qualitatively, but no quantitative correlation was evident between the SF <sub>6</sub> concentration and smoke intensity. Qualitative correlations were also found between the presence of SF <sub>6</sub> and optical density, and SF <sub>6</sub> concentrations and temperature.  The test data showed that the passive release mode, the dynamic release mode, and the fire tests ranked four different ventilation scenarios in the same order of effectiveness for the removal of smoke and SF <sub>6</sub> .					
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# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
in	inches	* 2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	6.5	square centimeters	cm <sup>2</sup>
ft <sup>2</sup>	square feet	0.09	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.8	square meters	m <sup>2</sup>
mi <sup>2</sup>	square miles	2.6	square kilometers	km <sup>2</sup>
acres	acres	0.4	hectares	ha
<b>MASS (WEIGHT)</b>				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
<b>VOLUME</b>				
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft <sup>3</sup>	cubic feet	0.03	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.76	cubic meters	m <sup>3</sup>

### TEMPERATURE (EXACT)

F	Fahrenheit temperature	S/9 (after subtracting 32)	Celsius temperature	°C
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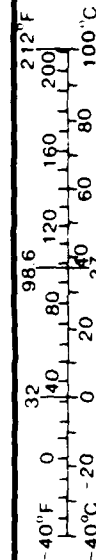
\* 1 in = 2.54 (exactly) For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price \$2.25. SD Catalog No. C13 10 286

## Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
<b>AREA</b>				
cm <sup>2</sup>	square centimeters	0.16	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	1.2	square yards	yd <sup>2</sup>
km <sup>2</sup>	square kilometers	0.4	square miles	mi <sup>2</sup>
ha	hectares (10,000 m <sup>2</sup> )	2.5	acres	ac
<b>MASS (WEIGHT)</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	st
<b>VOLUME</b>				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m <sup>3</sup>	cubic meters	35	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.3	cubic yards	yd <sup>3</sup>

### TEMPERATURE (EXACT)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
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## 1.0 INTRODUCTION

Fire at sea has always been one of the calamities most dreaded by seamen. Although significant improvements have been made during the last decade in both shipboard and shoreside firefighting capabilities, smoke continues to be one of the major difficulties in fighting shipboard fires. The dense smoke generated by shipboard fires not only creates a serious safety hazard for personnel trapped in the vicinity of the fire, but it also impairs the ship's survivability by reducing the visibility for firefighting personnel.

### 1.1 Background

Traditional damage control practices on board a ship normally require the securing of the heating, ventilation and air conditioning (HVAC) system upon detection of smoke or fire. This shutdown of the HVAC system retards the spread of the fire by reducing both the air supplied directly to the fire as well as limiting the transport of the fire by the exhaust system. Recent research efforts indicate that a higher level of safety both for personnel and ship survival may be provided by exhausting smoke and toxic gases with an integrated exhaust and smoke removal system. [1] These recent efforts call for the utilization of HVAC systems to create positive pressurizations in specific areas to minimize smoke migration into areas of higher pressures. These principles have been successfully demonstrated in buildings in past years and are now being incorporated into new building designs. This concept is now being considered for use on ships.

The U.S. Coast Guard is currently investigating the possibility of applying smoke control techniques to Coast Guard cutters. To date, this technique involves measuring the movement of room temperature air by using a detectable gas, sulfur hexafluoride ( $\text{SF}_6$ ). [2,3] This technique was previously evaluated under field conditions on an operational Coast Guard cutter and demonstrated that quantitative data on air flow characteristics of ventilation systems can be obtained. The testing was conducted on the 210

foot USCGC VIGOROUS (Figure 1) at the U.S. Coast Guard Academy in New London, Connecticut. Further testing is planned on other classes of Coast Guard cutters.

To date, a technique for determining hot smoke movement on ships has not been thoroughly researched and compared against the results of full scale fire tests. Methods which are both reproducible and accurate would be invaluable for testing and improving smoke control procedures aboard ships. If smoke movement can indeed be characterized, methods and procedures for effective smoke control could be evaluated for overcoming one of the major difficulties in shipboard fires.

### 1.2 Objective

The objective of this test program was to evaluate the suitability of  $SF_6$  as a tracer gas for determining smoke movement in ships. An integrated ventilation exhaust/collective protection system was used in investigative tests and full-scale shipboard fire tests to obtain data necessary to improve personnel safety and ship survivability during smoke involvement.

### 1.3 Smoke Movement

This project examines the problem of mapping smoke movement and does not attempt to quantify the production of smoke. Since smoke usually contains hot gases, buoyance is one of the two main factors that determine the movement of smoke from a fire. The second factor is the normal air movement due to temperature differentials, wind and the HVAC system. [4] Although the ventilation system has nothing to do with the fire, it can provide a means of carrying smoke through the ship. It would be expected that buoyancy effects will dominate close to a fire, and as the distance from the fire increases, normal air movements will dominate. One of the principles of smoke control requires a ventilation system that can create positive pressurization in areas used as escape routes. This requires that the ventilation system be able to create a higher pressure than that created by a fire in a compartment.



FIGURE 1. US Coast Guard Cutter *VIGOROUS*

It was found that protected areas require a minimum pressure of 0.15 inches of water to counter the pressure buildup of a fire. [5]

#### 1.4 SF<sub>6</sub> Characteristics

Sulphur hexafluoride (SF<sub>6</sub>) can be used as a means to identify air flow movement. The SF<sub>6</sub> is released into the air where it mixes quite thoroughly and easily. The air is then sampled and the resulting concentrations of SF<sub>6</sub> are used to map air flow patterns. For this reason, SF<sub>6</sub> is a good tracer gas and was selected as the tracer gas. This gas is colorless, odorless and detectable at levels down to one part per billion (ppb) by an electron capture detector. It has a molecular weight of 146.05 and a density of 0.382 pounds per cubic feet at 70°F (21.1°C) and 1 atm making it about five times as dense as air. Its viscosity at 88°F (31.1°C) is 0.0157 cp, a low value that makes it suitable for a gas-air tracer. The threshold limit value (TLV) is a measure of toxicity. The TLV for exposure to SF<sub>6</sub> is 1,000 part per million (ppm). This gas has, in fact, been described as a physiologically inert gas. Rats have been exposed to the maximum concentration of SF<sub>6</sub> possible without lowering the oxygen supply to an unsafe level (80% SF<sub>6</sub> and 20% O<sub>2</sub>) for periods of 16-24 hours. The rats showed no sign of intoxication, irritation or any other toxic effect, either during exposure or afterward. Since there is no health danger to personnel, SF<sub>6</sub> could be used on an operational vessel, and the movement could be traced without greatly disrupting shipboard routine.

Sulphur hexafluoride is an extremely stable gas. It does not react with water, alkali hydroxides, ammonia or hydrochloric acid. It is noncorrosive to any metal at ambient temperatures. Additionally, it is nonignitable and nonflammable. One of the largest uses of SF<sub>6</sub> is in gas-filled circuit breakers. It is also used in gas insulated transmission lines and electrical power-distribution substations. None of these are found in a normal shipboard environment. Hence, contamination by other SF<sub>6</sub> sources of samples collected on the test vessel is not expected.

## 2.0 APPROACH

All testing was conducted on the test vessel ALBERT E. WATTS (Figure 2) at the U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama. Three decks of the test vessel were used as a multi-level test citadel. The approach used in the SF<sub>6</sub> testing was to release the gas in the test compartment and measure the concentrations occurring at specified locations in the test citadel. The approach involved a passive, a dynamic, and a fire test phase. Each phase utilized a different driving force to disperse the SF<sub>6</sub> after it was discharged into the test compartment.

### 2.1 Test Citadel

The test citadel involved the main deck, 01 and 02 decks, (Figure 3) on the after deck house of the ALBERT E. WATTS. The 01 deck was designated as the release deck for the SF<sub>6</sub> and as the fire test deck. Compartment 01-5 was used as the SF<sub>6</sub> release compartment and the fire compartment for all tests. Two compartments and two passageways were located adjacent to the test compartment. The adjoining compartments were designated as compartments 01-6, and 01-7.

### 2.2 Fire Load

The fire load contained both Class A and Class B materials. The Class A combustibles for each fire test consisted of 260 pounds (117.9 kg) and contained:

* two sets of clothing	150 pounds (68 kg)
* books and publications	70 pounds (31.7 kg)
* miscellaneous woods	10 pounds (4.5 kg)
* plastic (PVC)	10 pounds (4.5 kg)
* electrical cable (in cable-way on overhead)	20 pounds (9.1 kg)



FIGURE 2. Test Vessel *ALBERT E. WATTS*



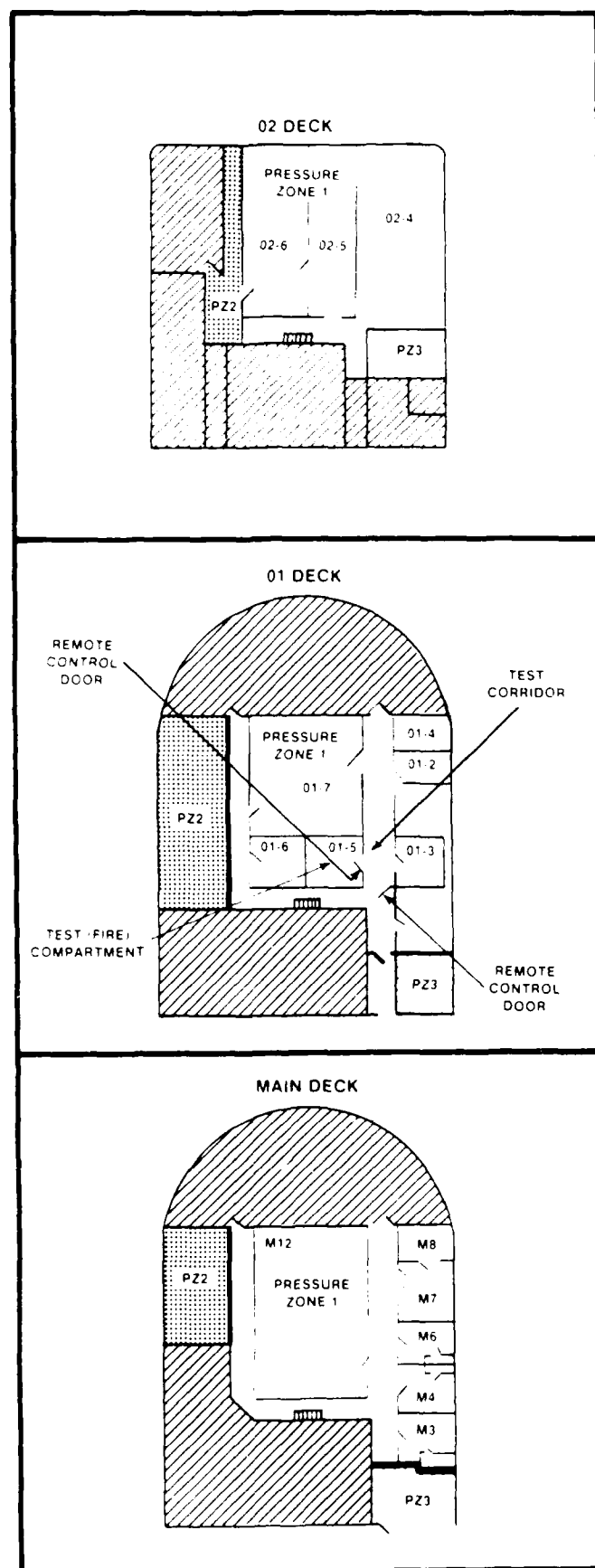


FIGURE 3. Test Citadel

The Class B combustibles for each fire test consisted of 1 gallon (3.8 l) of JP fuel and 1/2 gallon (1.9 l) of mineral spirits. The JP fuel was sprayed on the clothing for about 10 minutes from the overhead to simulate a small fuel leak. The mineral spirits were placed in a test pan under the fire load and used to ignite the clothing. Figure 4 illustrates the fuel load arrangement in the compartment before and after a fire test.

### 2.3 Ventilation

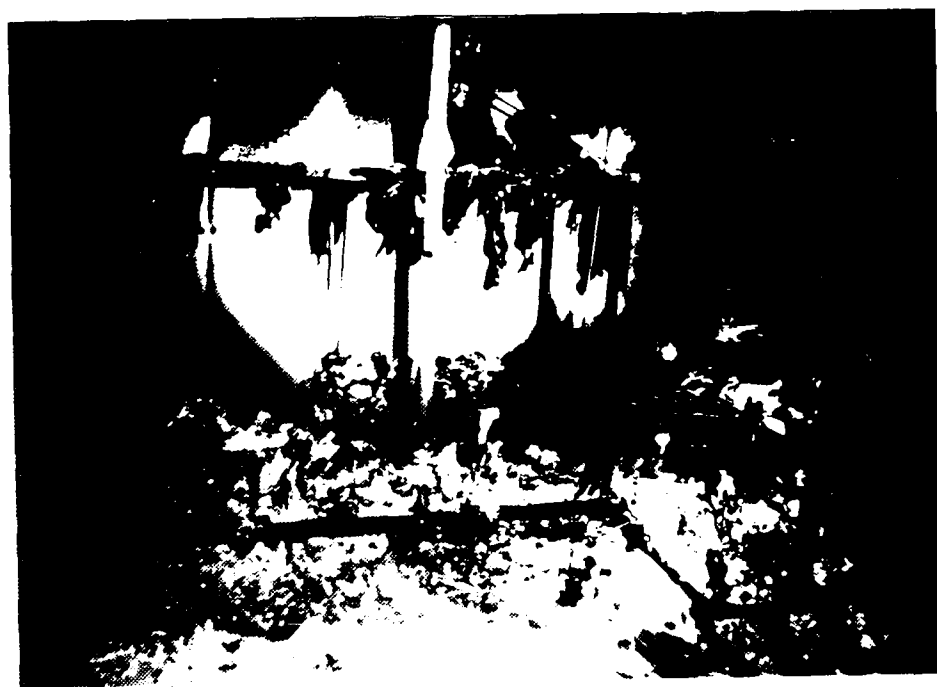
Ventilation in the citadel was scaled to provide the same air flow and volumes existing on a typical naval warship. The fire citadel was designated as pressure zone 1, with each deck being supplied fresh air from the same supply fan. Figure 5 shows a schematic of the supply/exhaust (smoke removal) systems. Pressure zone 1 contained three types of ventilation. These consisted of a supply system, an exhaust system, and a recirculation system. The duct network, the air distribution outlets, and their respective air flows for these three systems are shown in Figures 6, 7, and 8. The exhaust system also served as a smoke removal system.

### 2.4 Pressure Zones

The test citadel contained three pressure zones. As illustrated in Figure 6, the primary pressure zone contained the test compartment and was designated as pressure zone 1. This zone as well as pressure zones 2 and 3 (pz 2, pz 3) were pressurized to 2 inches (5.18 cm) of water to simulate ventilation pressures existing on U.S. Navy vessels. Pressure zones 2 and 3 were constructed around zone 1 as a buffer system to ensure that the pressure in zone 1 was maintained. Pressure zones 2 and 3 were pressurized by supply/exhaust systems independent of that used for pressure zone 1.

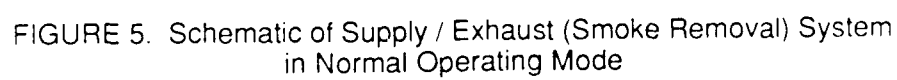


Before Test



After Test

FIGURE 4 Fire Load



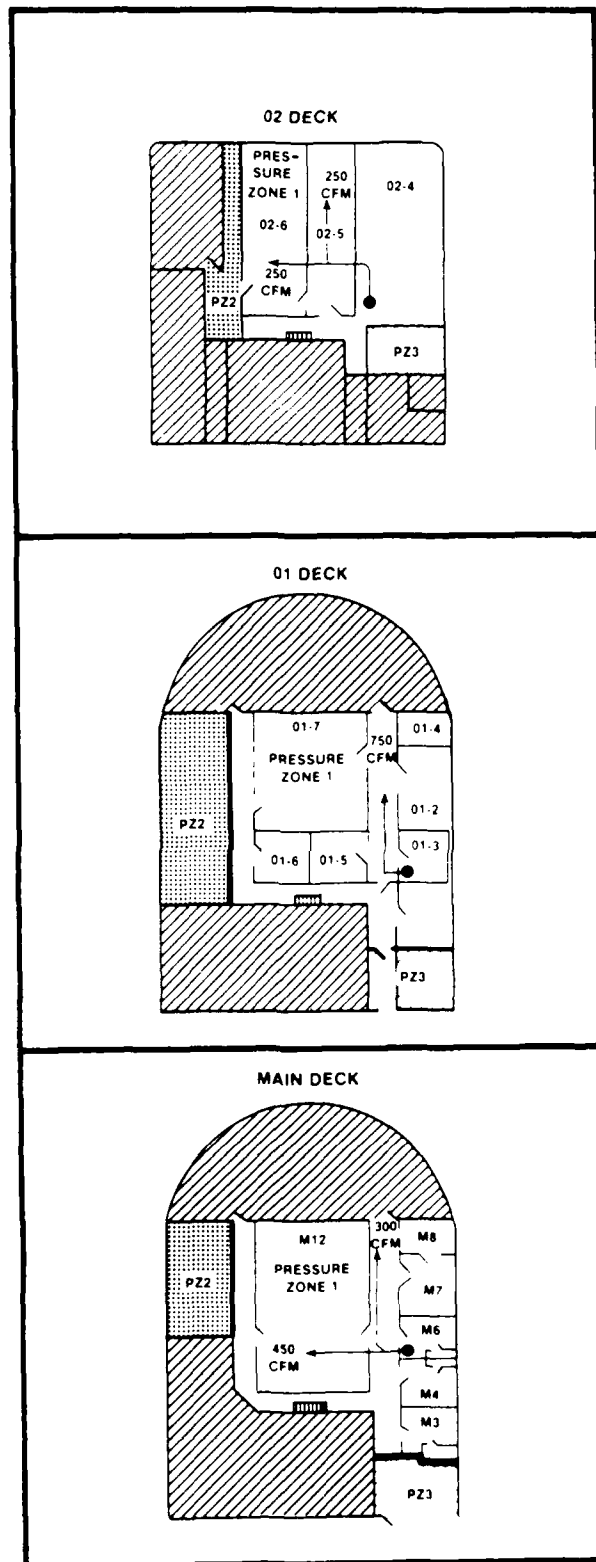


FIGURE 6. Supply System

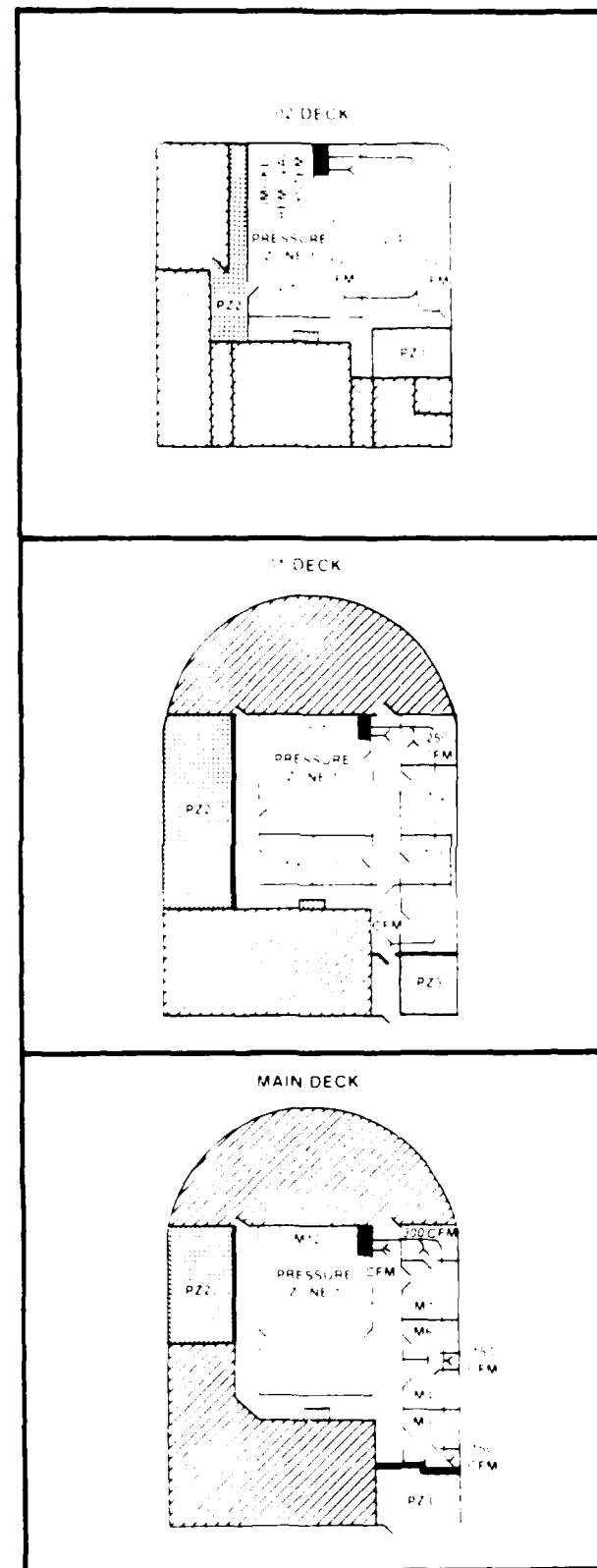


FIGURE 7. Exhaust (Smoke Removal) System

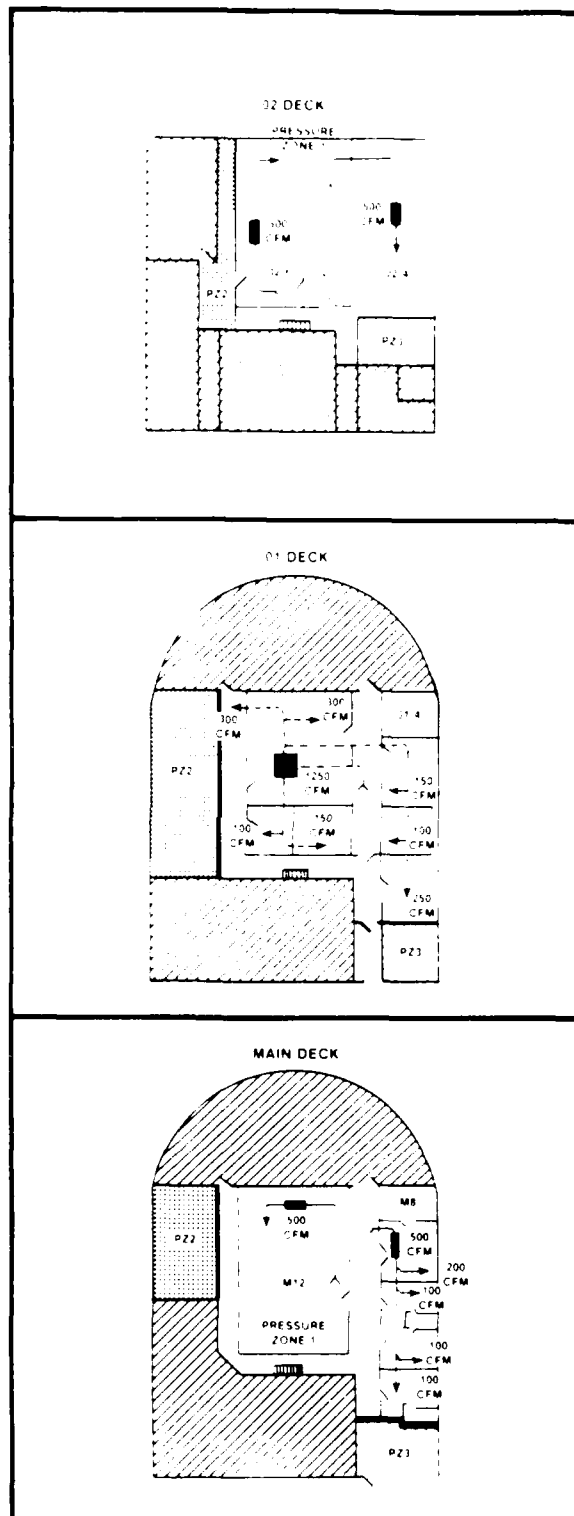


FIGURE 8. Recirculation System

### 3.0 TEST PROCEDURES

Four passive tests, four dynamic tests, and 12 fire tests were conducted to determine correlations between  $SF_6$  and smoke movement. During the passive tests the  $SF_6$  was released naturally into the test compartment so that the dispersion of the gas was dependent upon the air currents created by the ventilation scenario in effect. During the dynamic tests the tracer gas was released into the air flow of a variable speed high volume fan and then discharged into the test compartment. The flow rates of the fan were intended to simulate the buoyancy factor which would be created by the fires. The driving force behind the  $SF_6$  in the dynamic tests was the high volume fan and the ventilation scenario in effect. During the fire test the  $SF_6$  was released into the test compartment where the buoyant force of the fire and the ventilation scenario in effect was the driving force in dispersing the tracer gas.

#### 3.1 Test Preparation

The ambient condition in the test compartment was maintained as close as possible to 75°F (23.9°C) and 75% relative humidity. All doors leading to and inside the test area were closed and sealed. Videotape recordings and 35mm photographs were taken to document the appearance of the test compartment, fire load and instrumentation. This was accomplished before, during, and after each fire test.

Prior to the beginning of each test, all instrumentation was turned on for five minutes to establish baseline measurements. The simultaneous ignition and release of  $SF_6$  signaled the start of each fire test.

Data recording was accomplished by two different means. Computer collected data was recorded in an instrumentation trailer located on board a landing craft moored beside the test vessel. Wire leads and gas sampling tubes



led from the test area to the instrumentation trailer at the dock below.  $\text{SF}_6$  gas samples were collected in hand-held syringes and analyzed by a gas chromatograph after the test.

### 3.2 Test Sequence

All  $\text{SF}_6$  was released into the test compartment. The test fires were also conducted in this compartment. Pressurization throughout the entire citadel was maintained at between 0.5 and 2.0 inches of water for the duration of each test. At no time was the citadel pressurization allowed to drop to that of the outside atmosphere except for those tests where all ventilation was secured.

The general sequence of events was as follows:

- \* Test compartment door closed; passageway doors closed.
- \* HVAC system operating normally.
- \* Data acquisition system started five minutes prior to the test to collect background data.
- \* Release of  $\text{SF}_6$  and/or ignition of fire was designated as test time zero.
- \* Detection of fire by detector in passageway triggers alarm.
- \* At two minutes into the test, the ventilation was changed to the specific test ventilation scenario. This was the time that the smoke detector went off in the port passageway.
- \* The exhaust (smoke removal) scenario being used was operated for thirty minutes.
- \*  $\text{SF}_6$  was secured at 30 minutes into the test.
- \* In each test, data was collected for 60 minutes.
- \* At 60 minutes, each test was terminated.

Twenty tests were conducted according to four different ventilation scenarios. Each scenario utilized a different supply/exhaust (smoke removal) fan configuration. The four scenarios are described in Table I and the fan configurations are listed in Table II.

TABLE I  
VENTILATION SCENARIOS

- SCENARIO A     A fire alarm has been received from the smoke detectors located in passageway 01-11 and the smoke damper was actuated. Damage control personnel have secured supply system dampers on the 01 deck and all exhaust dampers in the main pressure zone. An electrical power failure is experienced and both the supply and exhaust fans are lost.
- SCENARIO B     A fire alarm has been received from the smoke detectors located in passageway 01-11 and the smoke damper was actuated. Due to battle damage both the supply system and exhaust system fans are inoperable. Damage control personnel have been unable to manually close the required dampers.
- SCENARIO C     A fire alarm has been received from the smoke detectors in passageway 01-11 and the smoke damper was actuated. Damage control personnel have aligned the ventilation system to the "standard smoke exhaust" configuration. Supply air to the 01 deck and exhaust air from the main, 01, and 02 decks has been secured. Both supply and exhaust fans are operable.
- SCENARIO D     A fire alarm has been received from the smoke detectors in passageway 01-11 and the smoke damper was actuated. Damage control personnel failed to align the ventilation system to the "standard smoke exhaust" configuration. Both the supply and exhaust system continue to operate.

TABLE II  
SUPPLY/EXHAUST (SMOKE REMOVAL) FAN CONFIGURATIONS

Test No.	Test Mode	Ventilation Scenario	Fire Load	Van. Fan Supply	CPS Supply System			Cen. Fan Exhaust	Exhaust-Smoke Removal System			Smoke Damper
					Main Deck	01 Deck	02 Deck		Main Deck	01 Deck	02 Deck	
1	Passive	B	--	Off	Open	Open	Open	Off	Open	Open	Open	Open
2	Passive	D	--	On	Open	Open	Open	On	Open	Open	Open	Open
3	Passive	A	--	Off	Open	Clsd	Open	Off	Clsd	Clsd	Clsd	Open
4	Passive	C	--	On	Open	Clsd	Open	On	Clsd	Clsd	Clsd	Open
5	Dynamic	B	--	Off	Open	Open	Open	Off	Open	Open	Open	Open
6	Dynamic	D	--	On	Open	Open	Open	On	Open	Open	Open	Open
7	Dynamic	A	--	Off	Open	Clsd	Open	Off	Clsd	Clsd	Clsd	Open
8	Dynamic	C	--	On	Open	Clsd	Open	On	Clsd	Clsd	Clsd	Open
9	Fire	A	260#/ 1-1/2 gal	Off	Open	Clsd	Open	Off	Clsd	Clsd	Clsd	Open
10	Fire	B	"	Off	Open	Open	Open	Off	Open	Open	Open	Open
11	Fire	C	"	On	Open	Clsd	Open	On	Clsd	Clsd	Clsd	Open
12	Fire	B	"	Off	Open	Open	Open	Off	Open	Open	Open	Open
13	Fire	A	"	Off	Open	Clsd	Open	Off	Clsd	Clsd	Clsd	Open
14	Fire	D	"	On	Open	Open	Open	On	Open	Open	Open	Open
15	Fire	A	"	Off	Open	Clsd	Open	Off	Clsd	Clsd	Clsd	Open
16	Fire	C	"	On	Open	Clsd	Open	On	Clsd	Clsd	Clsd	Open
17	Fire	D	"	On	Open	Open	Open	On	Open	Open	Open	Open
18	Fire	D	"	On	Open	Open	Open	On	Open	Open	Open	Open
19	Fire	C	"	On	Open	Clsd	Open	On	Clsd	Clsd	Clsd	Open
20	Fire	B	"	Off	Open	Open	Open	Off	Open	Open	Open	Open

Legend: CPS = Collective Protection System  
Van. Fan = Vaneaxial Fan  
Cen. Fan = Centrifugal Fan  
01 = 01 Deck Level  
P = Port Passageway Smoke Damper

### 3.3 SF<sub>6</sub> Release Rates

The flow rates of SF<sub>6</sub> into the test compartment differed for the passive release, dynamic release and actual fire tests. The rates for the different tests are described in the following paragraphs.

Although SF<sub>6</sub> has been described as a physiologically inert gas, prudence dictated that personnel exposure be kept to a minimum. Therefore, the intent was to minimize the amount of SF<sub>6</sub> to which the sample takers were exposed, yet maintain a high enough concentration that would be detectable in remote locations. The passive release resulted in the greatest accumulation of SF<sub>6</sub> in the test compartment. The pressure increase in the test compartment due to the release of the SF<sub>6</sub> was negligible but the gas flow did create a mixing of the SF<sub>6</sub>. Since the test compartment was not overpressurized, there was no driving force to push the SF<sub>6</sub> out into the passageway. The small amount of SF<sub>6</sub> recorded in the passageway was caused by seepage around the door and the action of the ventilation scenario drawing the SF<sub>6</sub> out of the test compartment. For Test 1, SF<sub>6</sub> in a concentration of 250 ppm was released as follows: 21 L/min for the first minute, then 15 L/min for the second minute and finally 6 L/min for the remaining 28 minutes. There was concern that this concentration might not produce distinguishable patterns. Consequently, for Tests 2, 3, and 4 the flow rate was increased to 32.6 L/min for the first minute, 23.3 L/min for the second minute and 9.3 L/min for the remaining 28 minutes.

Figure 9 shows the concentration of SF<sub>6</sub> at sample location A in the test compartment for Tests 1, 2, 3, and 4. It should be noted that the concentration of SF<sub>6</sub> for Tests 1 (fan scenario B) and 3 (fan scenario A) remain fairly constant after the SF<sub>6</sub> gas flow was turned off at minute 30. This indicated that the fan scenarios for these two tests had no effect on the removal of SF<sub>6</sub> from the test compartment. The concentration of SF<sub>6</sub> for Test 2 (fan scenario C) shows a steady decline after 28 minutes. This indicates that the fan scenario reduced the SF<sub>6</sub> concentration in the test compartment considerably. It is difficult to tell with Test 4 (fan scenario D) whether there is a decrease or if it remained fairly constant. The erratic

# SF6 TESTS

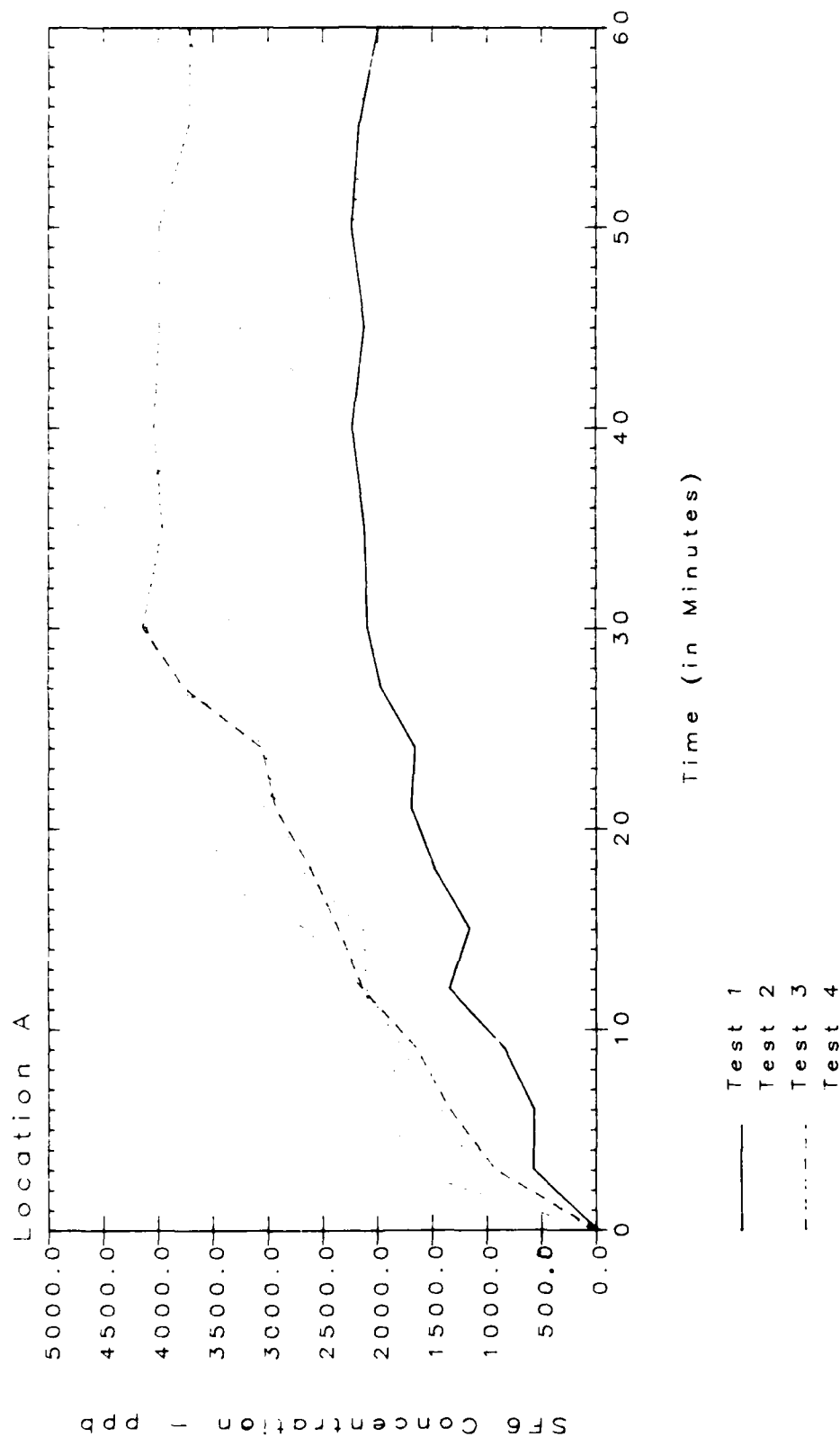


FIGURE 9. SF6 CONCENTRATION IN TEST COMPARTMENT -- PASSIVE RELEASE

behavior of the curve for Test 4 was attributed to movement in the fire compartment by the sample taker.

The flow rate of  $\text{SF}_6$  into the test compartment did not need to be as great for the dynamic release phase as it had been for the passive release phase. The centrifugal fan created pressurization in the test compartment that forced the  $\text{SF}_6$  out into the passageway. For all four tests in the dynamic release mode,  $\text{SF}_6$  in a concentration of 250 ppm was released as follows: 3.5 L/min for the first minute, 2.5 L/min for the second minute, and 1 L/min for the remaining 28 minutes. At the same time the centrifugal fan unit was set as follows: 521 cubic feet of air/min (cfm) for the first minute, 326 cfm for the second minute, and 130 cfm for the remainder of the time the fan was on.

Figure 10 shows the concentration of  $\text{SF}_6$  at sample location A in the test compartment for Tests 5, 6, 7, and 8. A comparison of Figures 9 and 10 shows the relative concentration of  $\text{SF}_6$  in the test compartment under the two different release modes. The release concentration of  $\text{SF}_6$  into the test compartment during the passive phase was 6-10 times as great as the release concentration in the dynamic phase. If the  $\text{SF}_6$  concentrations in location A were increased 6-10 times for the dynamic phase, the  $\text{SF}_6$  profiles would still be far less than those observed under the passive phase. This is attributed to the fan in the dynamic phase forcing the  $\text{SF}_6$  out of the test compartment.

There has been very little work done with releasing  $\text{SF}_6$  into an actual fire. Consequently, it was decided to use the first four fire tests to try different  $\text{SF}_6$  flow rates to begin a data base for future tests. In Test 9, 1.5 ml/min of pure  $\text{SF}_6$  was mixed with 9.3 L/min of compressed air and injected into the fire compartment for 30 minutes. Compressed air was added to pure  $\text{SF}_6$  to establish a driving force comparable to that of the previous  $\text{SF}_6$ /air mixtures. In Test 10, pure  $\text{SF}_6$  was released as follows: 3.5 ml/min for the first minute, 2.5 ml/min for the second minute and 1.5 ml/min for the remaining 28 minutes. This pure  $\text{SF}_6$  was mixed with compressed air that was released at a steady 4.5 L/min for 30 minutes. In Test 11, pure  $\text{SF}_6$  was released as follows: 10.5 ml/min for the first minute, 7.5 ml/min for the second minute and 3.0 ml/min for the remaining 28 minutes. This  $\text{SF}_6$

# SF6 TESTS

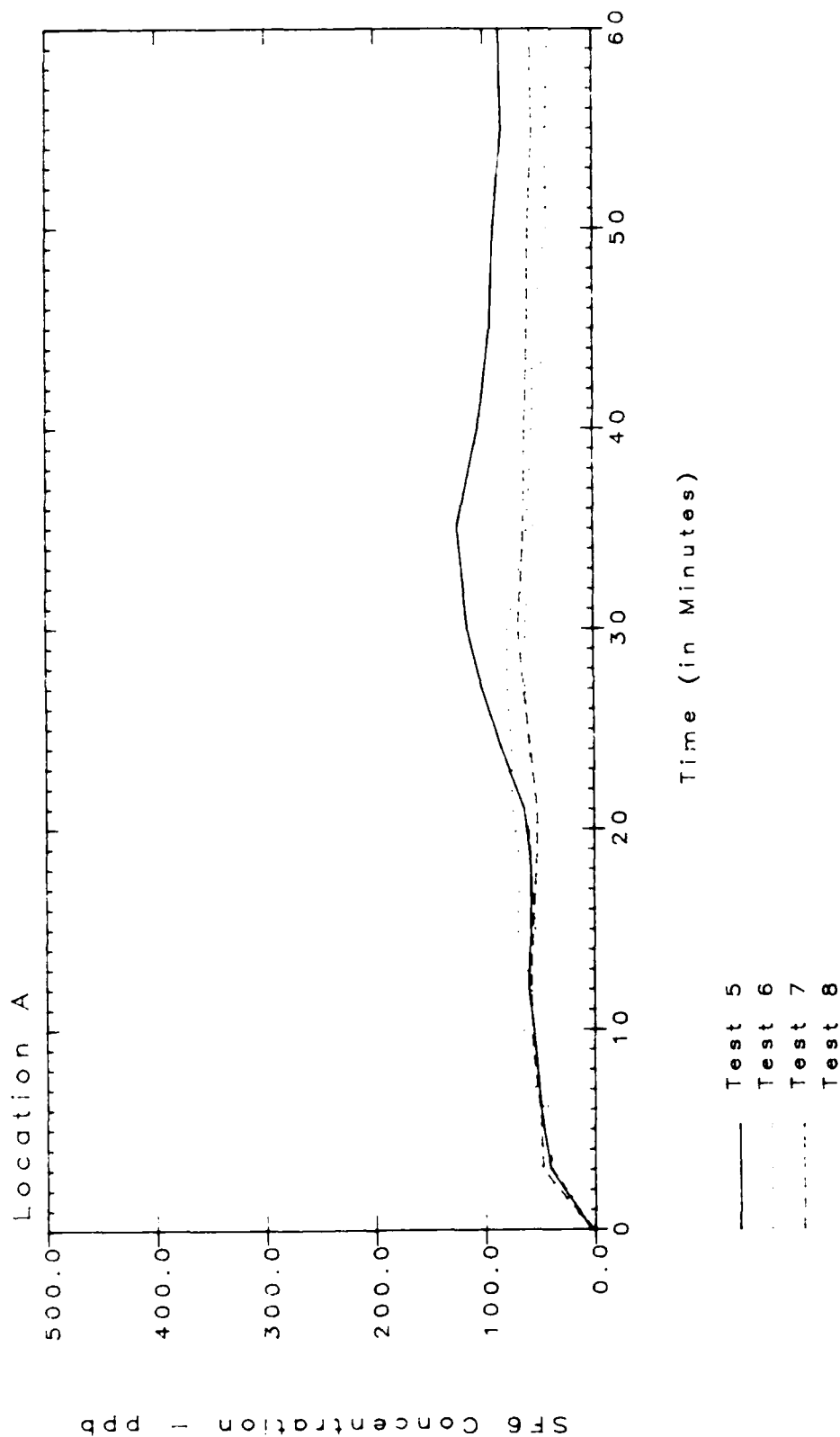


FIGURE 10. SF6 CONCENTRATION IN TEST COMPARTMENT -- DYNAMIC RELEASE

was mixed with compressed air as follows: 32.6 L/min for the first minute, 23.3 L/min for the second minute and 9.3 L/min for the remaining 28 minutes. Test 12 used the same release of pure  $\text{SF}_6$  as Test 10, 3.5 ml/min for the five minute, 2.5 ml/min for the second minute and 1.5 ml/min for the remaining 28 minutes. The flow rate of compressed air, however, was at 9.3 L/min for the 30 minute test. For the remaining eight fire Tests, 13-20,  $\text{SF}_6$  in a concentration of 60 ppm was released as follows: 14.6 L/min for the first minute, 10.4 L/min for the second minute and 4.2 L/min for the remaining 28 minutes.

### 3.4 Sample Collection

$\text{SF}_6$  concentrations in the passive and dynamic tests were measured at seven locations in the test citadel at three minute intervals for 30 minutes then at five minute intervals for another 30 minutes. Four additional locations were sampled at 15 minute intervals. The 15 minute collection points I, J, K, and L were located at areas where  $\text{SF}_6$  was expected to appear in very limited quantities. The  $\text{SF}_6$  sampling points are shown in Figure 11. Sample A was collected at a 48 inch (121.9 cm) height. Samples B, D, G, J, and L were taken at a 24 inch (61.0 cm) height. Samples C, E, I, K, and F were recorded at approximately a 72 inch (182.9 cm) height.

$\text{SF}_6$  concentrations in the fire tests were measured at 5 locations at five minute intervals for 60 minutes. After 30 minutes, the ventilation mode was changed to several different configurations in an attempt to quickly remove all smoke from the test citadel. Therefore, only the first 30 minutes for each fire test will be addressed in this report. The sample locations for the fire tests were A, B, C, D, and E. Syringe samples for the fire tests were collected from a piping system which constantly withdrew gas from the five sampling points. The piping was special tubing which did not effect the results of the samples being collected.



### Sample Height off Deck

	Inches	Cm
I	72	182.9
J	24	61.0
A	48	121.9
B	24	61.0
C	72	182.9
D	24	61.0
E	72	182.9
F	72	182.9
G	24	61.0
L	24	61.0
K	72	182.9

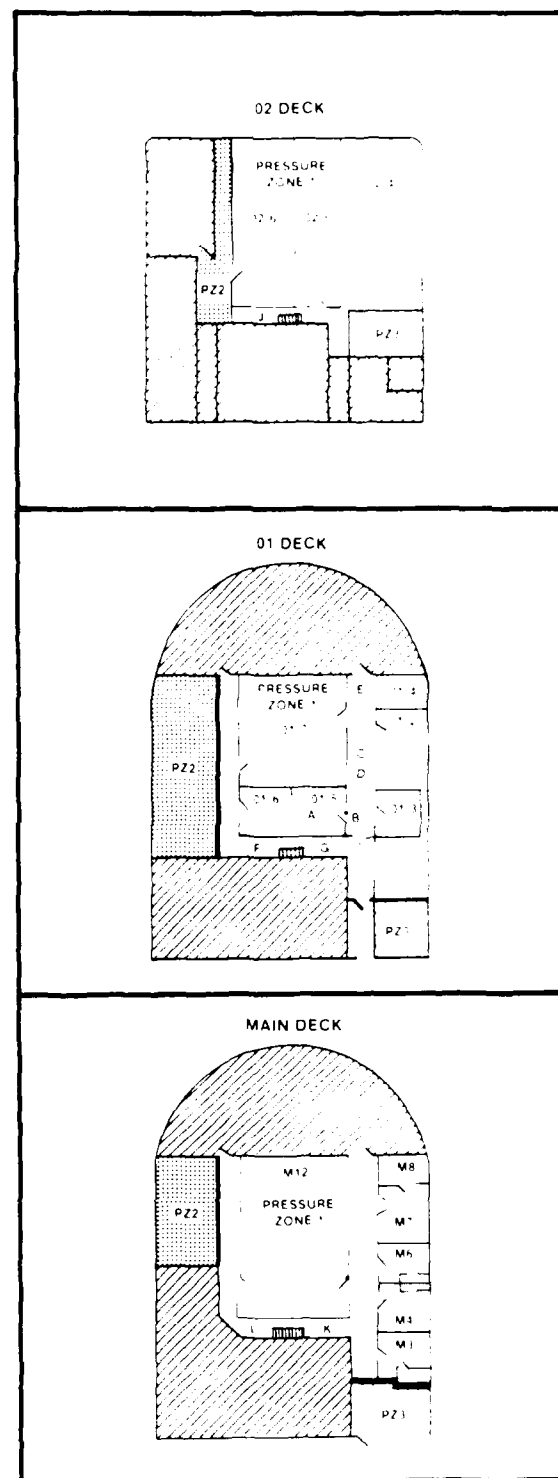


FIGURE 11. SF<sub>6</sub> Sampling Points

Fifty milliliter air samples were collected in disposable syringes during the passive and dynamic tests at different locations and heights in the test citadel. The samples were collected by personnel (Figure 12) instructed in the procedure of sample collection. A public address system was used to inform the individuals when to collect samples. Thirty seconds was a standard time needed to fill a sample syringe.

For each test, between 120 and 130 samples were taken. The syringes were capped, marked, and brought back to a central room to be analyzed. The concentration of  $SF_6$  in the air samples was measured by a portable gas chromatograph. It was fitted with a 0.25 ml sampling loop and an electron capture detector with a 200 ml tritium source. The instrument was calibrated before and after each test by standard  $SF_6$ /air mixtures. The output of the instrument was recorded by a reporting integrator.

### 3.5 Additional Instrumentation

In addition to the primary  $SF_6$  data, the instrumentation described in the following paragraphs was also used to collect test data. This data was then recorded by a computerized data acquisition system as illustrated in Figure 13. Those parameters affecting  $SF_6$  and other smoke movement will be discussed in detail in Sections 4 and 5.

Portable instruments were used to measure background environmental conditions before and after the fires. This included a recording barometer and a recording hygrothermograph in the passageway aft of the test compartment.

Temperatures were measured in compartments throughout the test citadel by using vertical strings of inconel sheathed thermocouples (Type K). Each string consisted of three thermocouples spaced at 24, 48, and 72 inches (61.0, 121.9, 182.9 cm) above the deck. Two thermocouples were also located in the ventilation system. One was placed in the supply duct and one in the exhaust (smoke removal) duct.



Test Compartment



Test Passageway

Figure 1. Test Compartment and Test Passageway

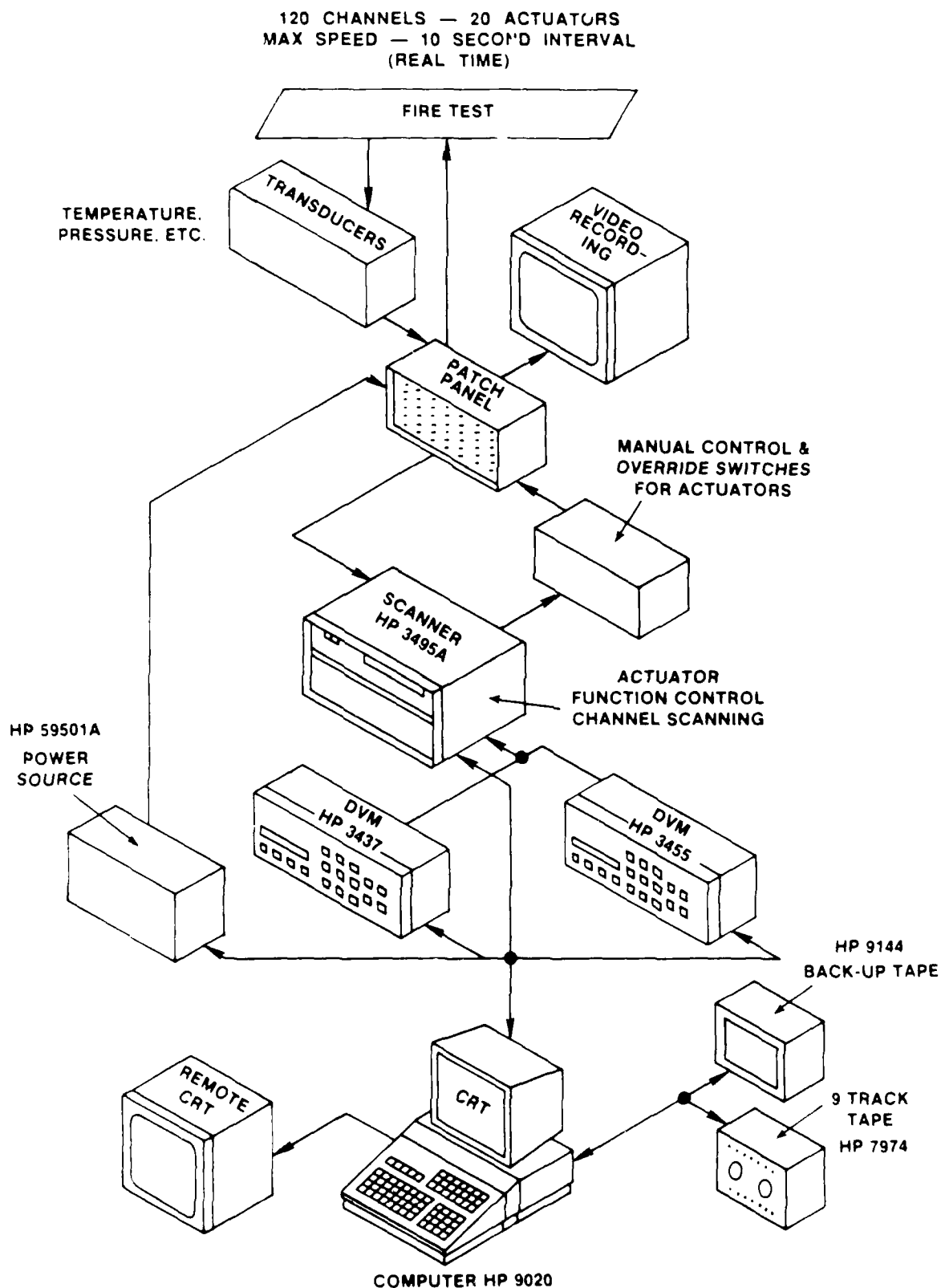


FIGURE 13. Marine Fire Research Data Acquisition System

Total heat flux was determined by four calorimeters. One was centered in the overhead of the fire compartment while the other three were centered in the after bulkhead of the fire compartment at heights of 24, 48 and 72 inches (61.0, 121.9, 182.9 cm).

Five pressure transducers were used to measure the differential pressure in the three pressure zones and normal atmospheric pressure. Three pressure transducers were set up inside the test citadel, one inside each deck level. The fourth pressure transducer was set up in pressure zone 2 at the 02 level while the fifth pressure transducer was set up in pressure zone 3 on the 02 level.

Bi-directional velocity probes were used to measure air flow at the following locations: geometric center of the vertical duct for the integrated supply/exhaust (smoke removal) system, louvers in test compartment door, and in the test passageway at four locations in a vertical string located 15.25 feet (4.6 m) aft of the center of the fire compartment door.

Oxygen, carbon dioxide, and carbon monoxide were measured in the center of the passageway at a height of 48 inches (121.9 cm) at a point 15.25 feet (4.6 m) aft of the center of the test compartment door. These gases were also measured at the center of the after bulkhead of the test compartment at heights of 24 and 72 inches (61.0, 182.9 cm).

Smoke obscuration was measured by using single and vertical strings of low-powered laser emitters (0.5 mW at 0.632 micron wavelength) with associated photo-diode detectors. Strings consisted of two lasers positioned at 24 and 72 inches (61.0, 182.9 cm) above the deck and three lasers positioned at 24, 48 and 72 inches (61.0, 121.9, 182.9 cm) above the deck. Laser light from any emitter that reached the opposite side of the passageway or compartment was transmitted to its associated photodiode detector through fiber optic cables. This was done to remove the electronics from the heat affected zone. Lasers were placed at the following locations:

One laser and detector was positioned on the main deck to determine obscuration along the stairwell at the approximate height of a handrail.

One laser and detector was positioned on the 01 level to determine obscuration along the stairwell at the approximate height of a handrail.

One laser with a detector was used to measure the smoke build-up within the fire compartment.

One string of three lasers and detectors was aimed across the passageway just aft of the test compartment and compartment 01-3.

Two lasers mounted on the port side of passageway (01-11) on the 01 level 24 and 72 inches (61.0, 182.9 cm) above the deck. The receivers were mounted at the forward end of the fire deck and the emitters were mounted at the aft end of the fire deck.

Three lasers mounted on the starboard side of passageway (01-11) on the 01 level 24 and 72 inches (61.0, 182.9 cm) above the deck. The receivers were mounted at the forward end of the fire deck and the emitters were mounted at the aft end of the fire deck.

Four color video cameras with recorders were used to record each test on 60 minute video tapes. One video camera was located on the weather deck of the ALBERT E. WATTS to record smoke exhausting from the integrated exhaust and smoke removal system. A second video camera was mounted on the watertight door on the 01 level to record smoke in the 28 foot (8.5m) passageway outside of the test compartment. The watertight door was modified to accommodate this camera by including a protective hood, camera mounting bracket, and a 6 by 24 inch (15.2 by 61.0 cm) high viewing port. The third video camera was positioned in room 01 to record personnel and/or smoke on the ladder between the 01 level and 02 level in pressure zone #1. One video camera was located aft of the test compartment to record the fire and associated smoke within it.

Two hand-held 35 mm cameras were used to document all testing. They were used to photograph instrumentation setup and to supply photographs of all test equipment. This also included the fire load before and after each test.

A fully portable gas chromatograph equipped with an election capture detector was used for examining the sulfur hexafluoride content of the grab samples. The gas chromatograph was also equipped with a gas sampling valve to insure reproducible injections of test samples. A reporting integrator was connected to the gas chromatograph for peak identification and for quantitative calculations. The gas chromatograph permitted the capability for identifying sulfur hexafluoride while the election capture detector provided a means for measuring low concentrations of the gas. The integrator provided a means for recording the gas concentrations.

#### 4.0 EXPERIMENTAL RESULTS

The test data was analyzed to identify parameters influencing the movement of the  $\text{SF}_6$ . These parameters were pressure, temperature, optical density and smoke obscuration. All tests were 60 minutes in duration. During the actual fire tests once the  $\text{SF}_6$  was secured at minute 30 and other experiments were initiated that affected the collected data. Consequently, only the first 30 minutes of data will be presented in this report for Tests 9-20.

##### 4.1 Pressure

The current philosophy aboard ships when a fire occurs is to secure both the supply and exhaust fan and to close the smoke dampers on all levels. This action when modified for scenarios A and B resulted in a pressure drop in pressure zone 1 to atmospheric or 0 inch water gauge (wg). In this existing pressure condition, the buoyancy force of the fire was sufficient to drive  $\text{SF}_6$  out of the test compartment, through the test corridor and into the athwartship passageway. Figure 14 shows the presence of considerable  $\text{SF}_6$  on

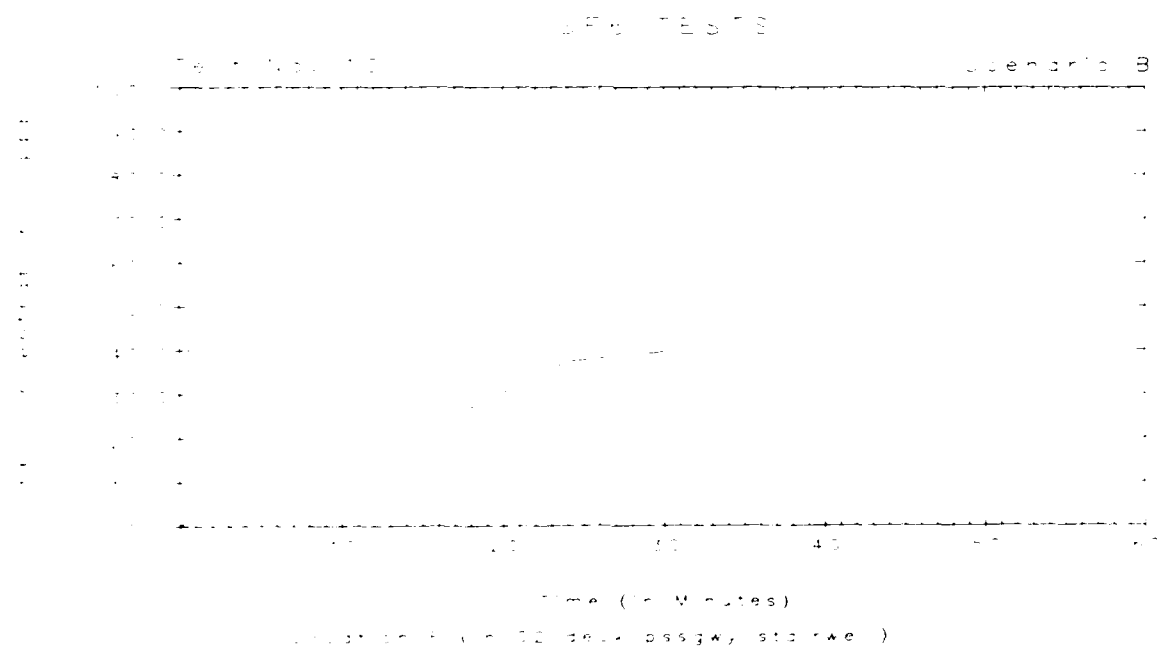
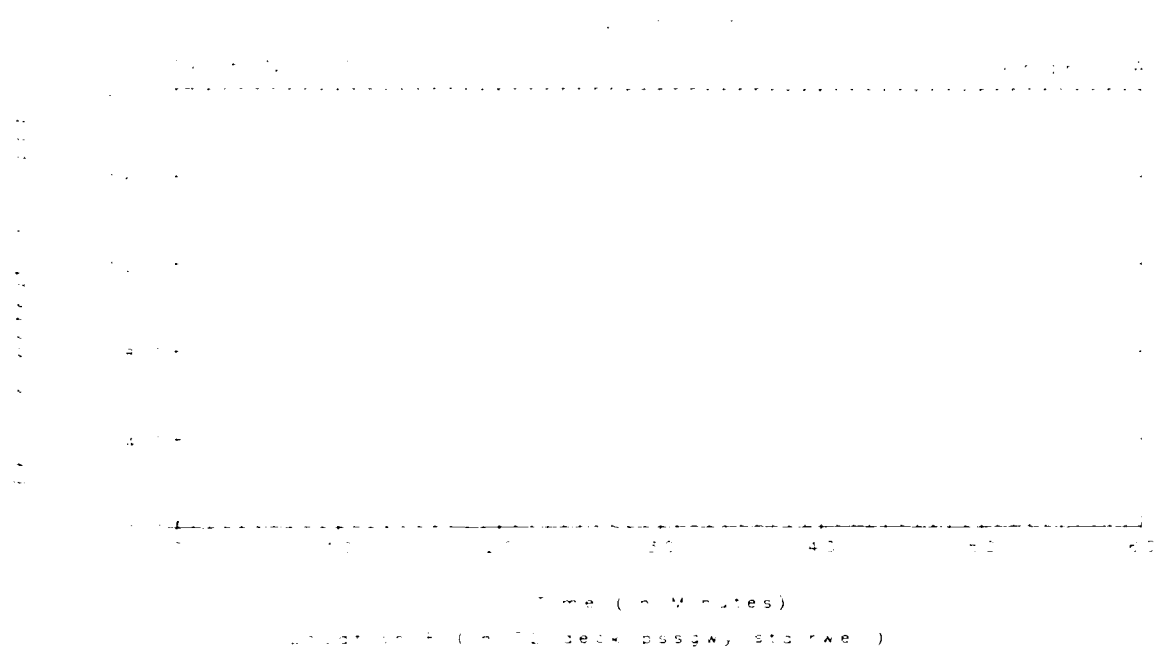


FIGURE 14. SF<sub>6</sub> Concentration at Location F for Scenarios A and B



the 02 deck above the stairwell and is representative of the three tests in scenarios A and B. There was no  $SF_6$  recorded above the stairwell on the main deck for the tests in scenarios A and B. It appears that the driving force of the fire came to an end at the athwartship passageway and the  $SF_6$  followed the buoyancy of the hot smoke in rising up the open stairwell to the 02 deck.

A positive pressure of about 0.7 inch (1.78 cm) water gauge was maintained in pressure zone 1 during scenarios C and D as a result of their supply/exhaust fan configuration. Although the supply fan was not discharging air to the fire deck in scenario C as it was in scenario D, it was still discharging air to the main deck and the 02 deck. The presence of  $SF_6$  in Figure 15 on the 02 deck indicates that the supply air flowing into the 01 deck through the open stairwell from the 02 deck was not sufficient to block the rise of all  $SF_6$  mixed with hot smoke. Figure 15 is representative of the  $SF_6$  concentration on the 02 deck for all tests in scenarios C and D. There was no  $SF_6$  detected below the stairwell on the main deck for scenarios C and D. The quantity of  $SF_6$  in scenarios C and D on the 02 deck above the stairwell was nearly unmeasurable when compared to the large quantities of  $SF_6$  recorded in the same locations for scenarios A and B.

The occurrence of  $SF_6$  above the open stairwell in the 02 deck in all four scenarios and the fact that it was not found below the stairwell on the main deck strongly indicates that once the driving force of the fire is removed that the  $SF_6$  follows the tendency of hot smoke to rise in an enclosed area.

#### 4.2 Temperature

Temperatures occurring as a result of the fire tests created a buoyancy force which propelled smoke particles and the  $SF_6$  away from the fire source. The hotter the compartment temperatures, the greater the driving force, hence the greater the concentration of smoke and  $SF_6$  forced out of

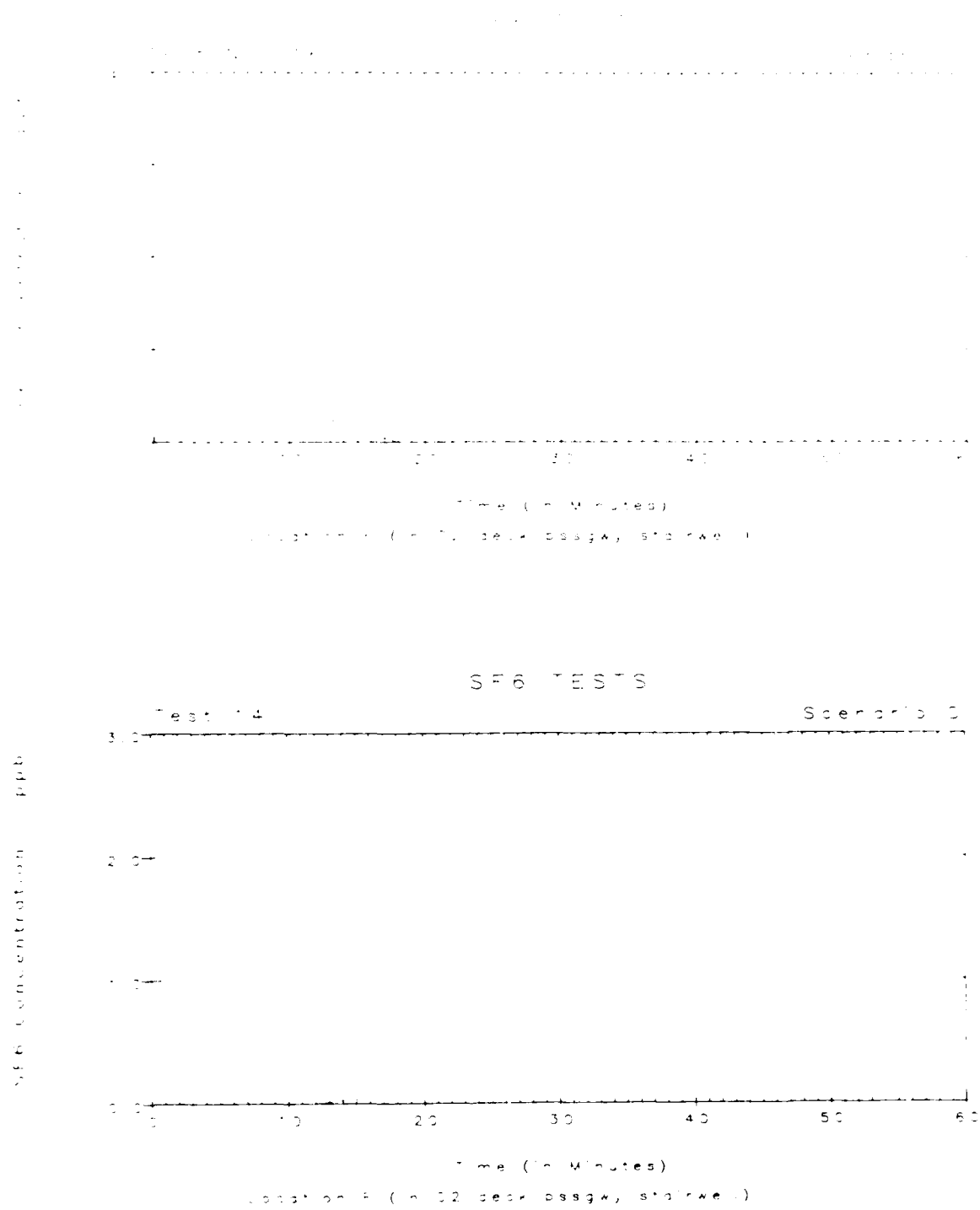


FIGURE 15. SF<sub>6</sub> Concentration at Location F for Scenarios C and D

the test compartment into the adjacent test passageway. This is verified when we look at the increased concentration of the  $SF_6$  profiles of the test passageway for a test scenario which has high temperatures inside the test compartment when compared to the  $SF_6$  profiles of a fire test scenario which had low temperature profiles inside the test compartment. Figure 16 shows high temperature histories in three fire tests at a 72 inch (182.9 cm) height for scenario A and lower temperature histories for the same height for three fire tests in scenario D. If we compare the qualitative values of the  $SF_6$  profiles for any test in scenario A (high temperatures) against the  $SF_6$  profiles in any test for scenario D (low temperatures) we see higher  $SF_6$  values (Figure 17) in the passageway when the compartment temperature is hotter. This indicates that hotter temperatures produce a greater driving force and move more  $SF_6$  out of the test compartment than does lower temperatures.

It is interesting to note that for the hotter tests in scenario A the test video tapes show immediate smoke obscuration of the passageway along with high values of  $SF_6$ . In the relatively cooler tests of scenario D the video tapes indicate smoke obscuration of the passageway at the 30 minute mark along with low values of  $SF_6$ . This video data verifies the effect that temperature has on the movement of  $SF_6$ .

#### 4.3 Optical Density/Smoke Obscuration

This section compares the optical density data measured by lasers with smoke obscuration data collected by a video camera and a recorder. The optical density data was collected at three heights (24, 48, and 72 inches) (61.0, 121.9, and 182.9 cm) looking across the test corridor just aft of the test compartment.

Prior to the testing three 25 watt incandescent lamps were located at different locations and heights down the test corridor to provide a means for observing smoke buildup. The lamps were intended to provide a means to check the results of the optical density data and to provide comparison data between

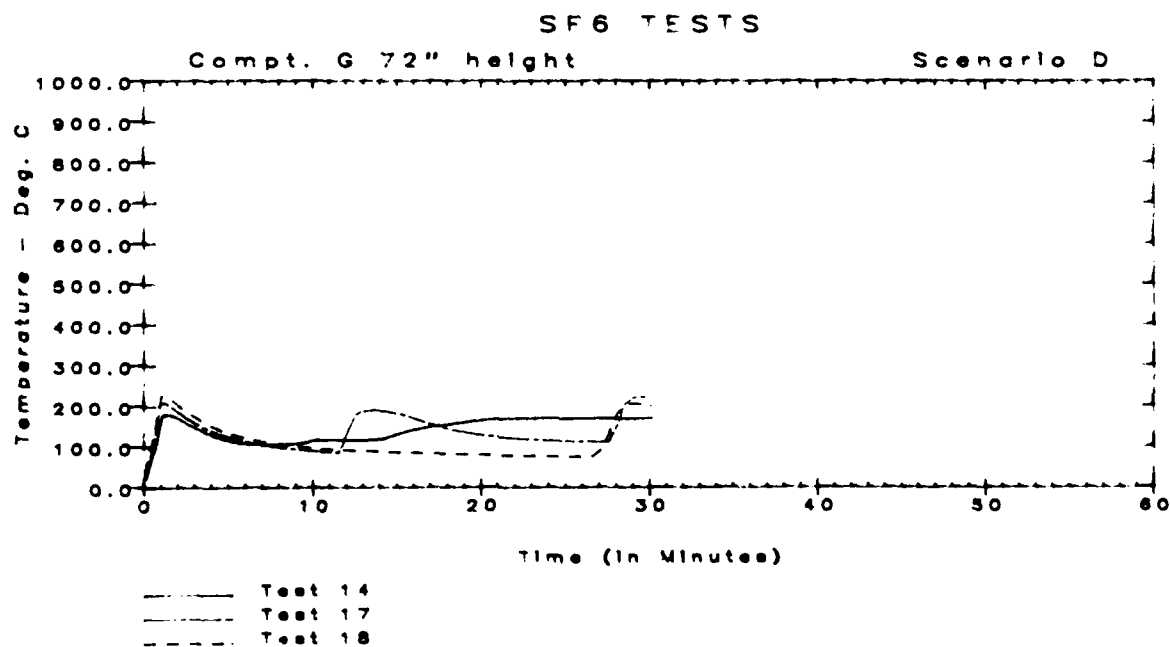
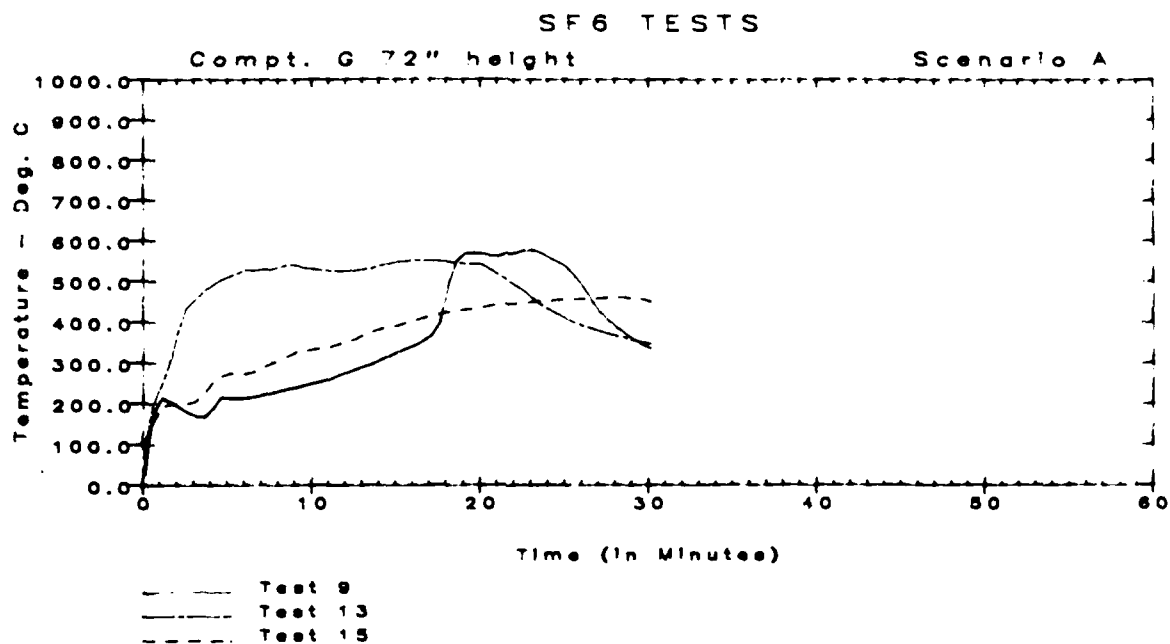


FIGURE 16. Compartment Temperatures for Scenarios A and D

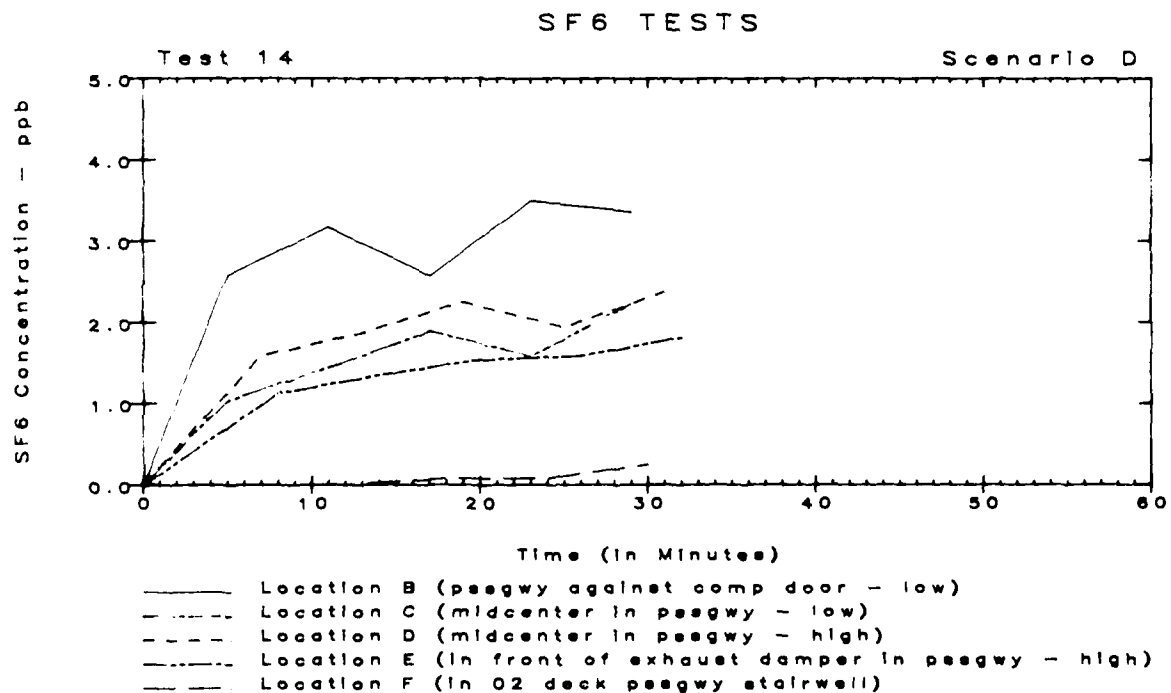
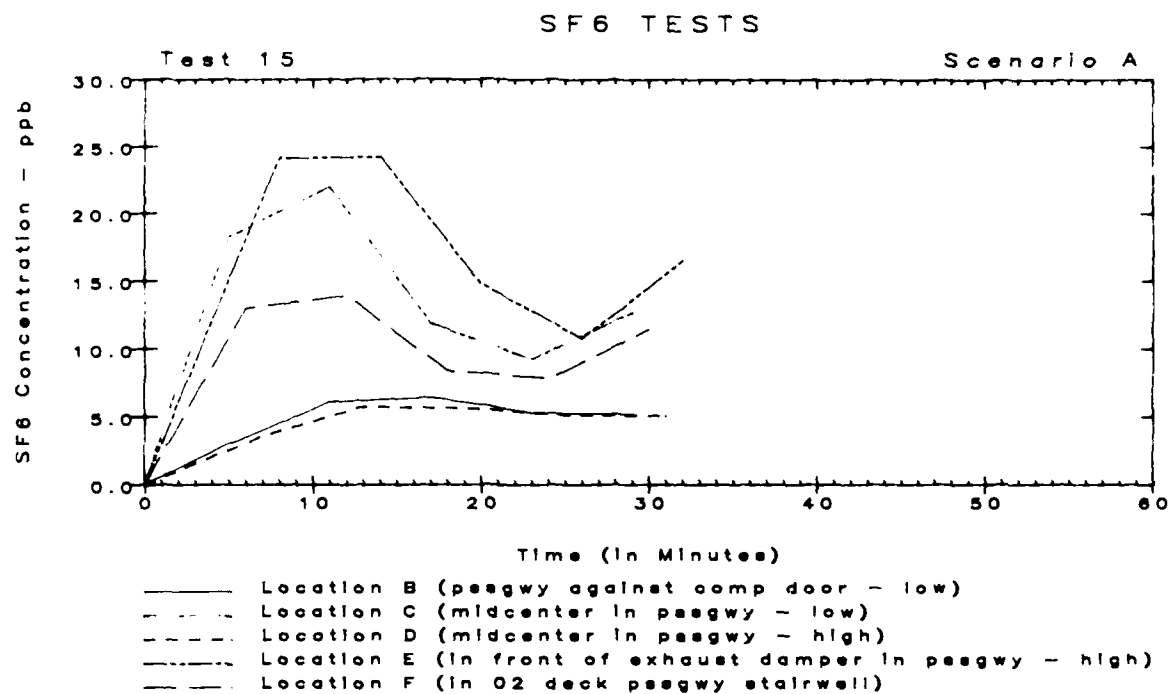


FIGURE 17. SF6 Profiles in Test Corridor for Scenarios A and D

different test fan scenarios. Figure 18 shows the location of the lamps in the test corridor. The smoke obscuration data (Table III) was obtained by viewing video tapes from a video camera which monitored the entire test corridor from aft to forward.

The test tapes were reviewed by one individual at a single setting to eliminate as much human error as possible in recording the visual smoke obscuration data. This was repeated a second time as a check on the first observations made from the tapes. A Trinitron Sony 25 inch (63.5 cm) color monitor and a Sony Umatic videocassette recorder were used to review and to playback the 3/4 inch (1.9 cm) Umatic test tapes. Before the tapes were reviewed, a colorbar was used to adjust the monitor. No further adjustments were performed once the viewing process was started. Each video tape had been imprinted with a time-date generator during the testing so that all observations were made from actual test times.

If we take the test times in Table III when the corridor lamps were obscured by smoke and compare this to the optical density values at the same test times, we find that an optical density of 0.25 indicates smoke so thick in the corridor that the lamp nearest that laser height becomes totally obscured from vision on the video test tape. This can be verified by plotting lamp data in Table III onto the optical density plots in Figure 19 for Test 9 and 10. This correlation is valid not only for all tests in scenario A and all tests in scenario B but is true for the other tests in the other scenarios. Tests 14 and 16 in Figure 20 are examples showing that the other test scenarios indicate this same correlation. The correlation between the same time when the lamps are no longer visible by video and the occurrence of the same optical density value of 0.25 for each test indicates that the optical density measurements are accurate.

#### 4.4 Optical Density/SF<sub>6</sub>

Figures 21 - 24 show optical density and SF<sub>6</sub> data collected in the test corridor for a fire test of each scenario. When one compares the overall pattern of the optical density profiles to the overall pattern of the SF<sub>6</sub>

TABLE III  
SMOKE DATA FROM VIDEO CAMERA MONITORING TEST CORRIDOR

Scenario	Test	Time when Lamps are Obscured by Smoke in Passageway (Minutes/Seconds)			General Description of Smoke in Passageway (See Legend)	Optical Density When Lamp Obscured by Smoke
		Lamp 1	Lamp 2	Lamp 3		
A	9	2:35-30:00	3:30-30:00	4:00-30:00	Extreme	0.25
	13	0:48-30:00	1:10-30:00	2:40-30:00	Extreme	0.25
	15	2:30-30:00	5:25-30:00	6:00-30:00	Extreme	0.25
B	10	13:20-14:00 24:00-30:00	27:00-30:00	28:00-30:00	Extreme	0.25
	12	2:40-30:00	3:28-30:00	3:55-30:00	Extreme	0.25
	20	Visible	Visible	Visible	Slight	--
C	11	14:30-16:00 28:00-29:00	10:30-11:00	Visible	Heavy	0.25
	16	2:00-12:00 16:00-30:00	Visible	Visible	Heavy	0.25
	19	Visible	Visible	Visible	Moderate	--
D	14	Visible	Visible	Visible	Moderate	--
	17	1:05-2:00 12:00-12:30 28:00-28:45	Visible	Visible	Heavy	0.25
	18	Visible	Visible	Visible	Moderate	--

Legend: Slight = Smoke noticeable, but all lamps still visible  
Moderate = Smoke obscures one lamp  
Heavy = Smoke obscures two lamps  
Extreme = Smoke obscures three lamps

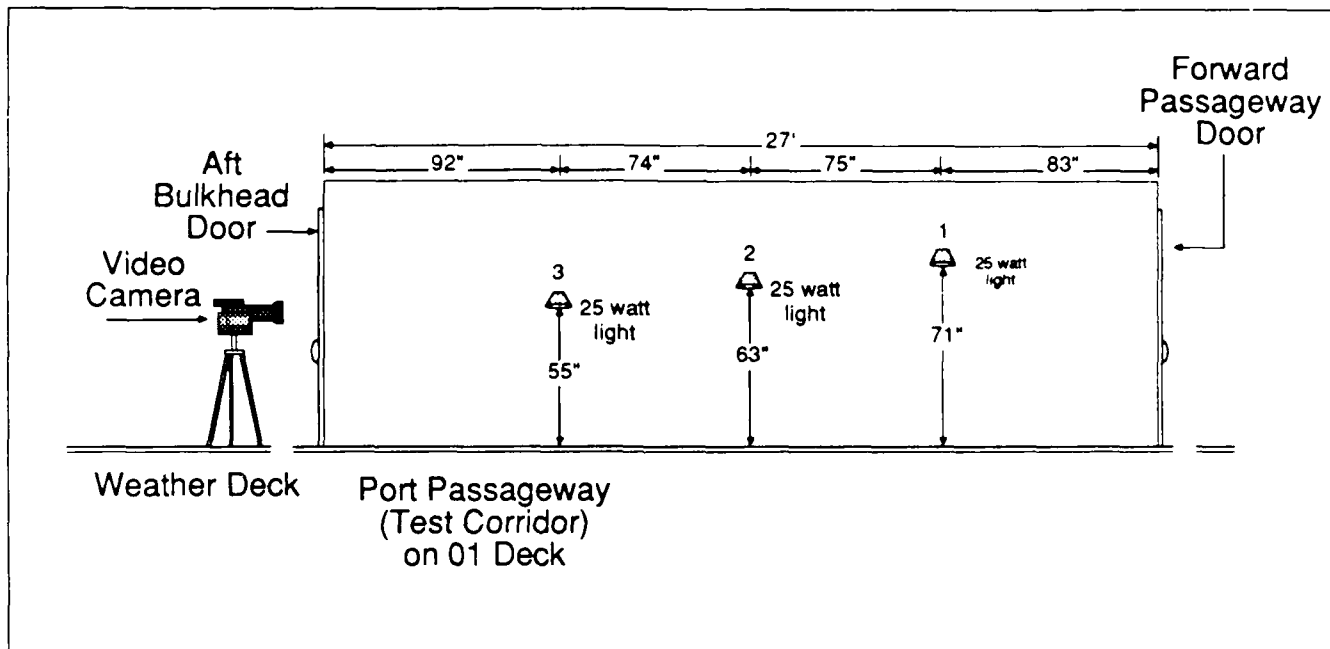
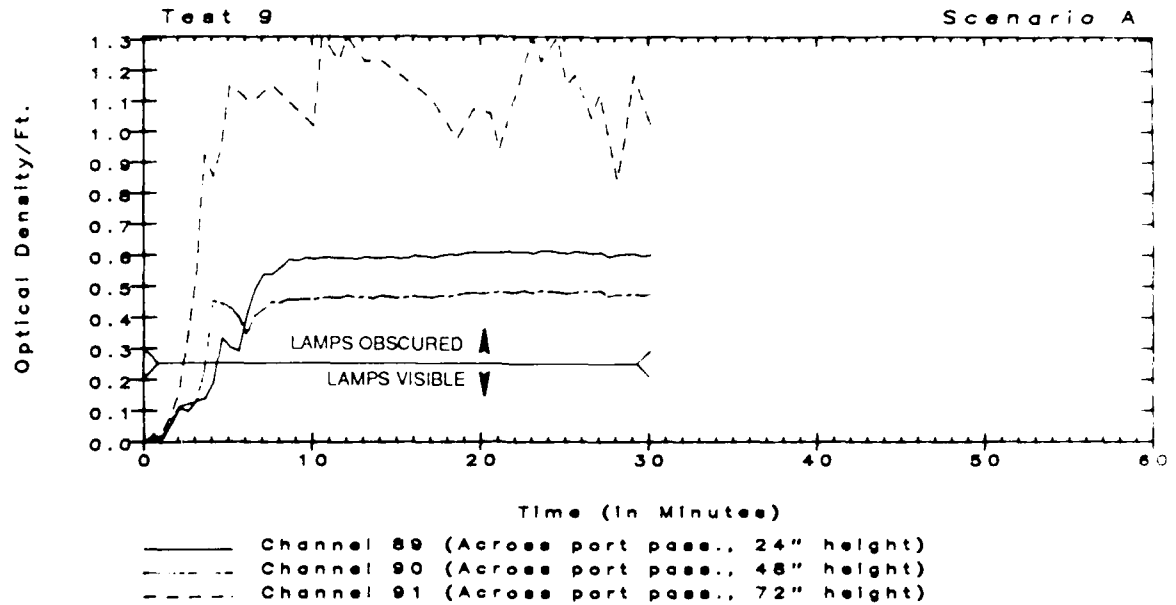


FIGURE 18. Lamp Installation in Test Corridor



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# SF6 TESTS

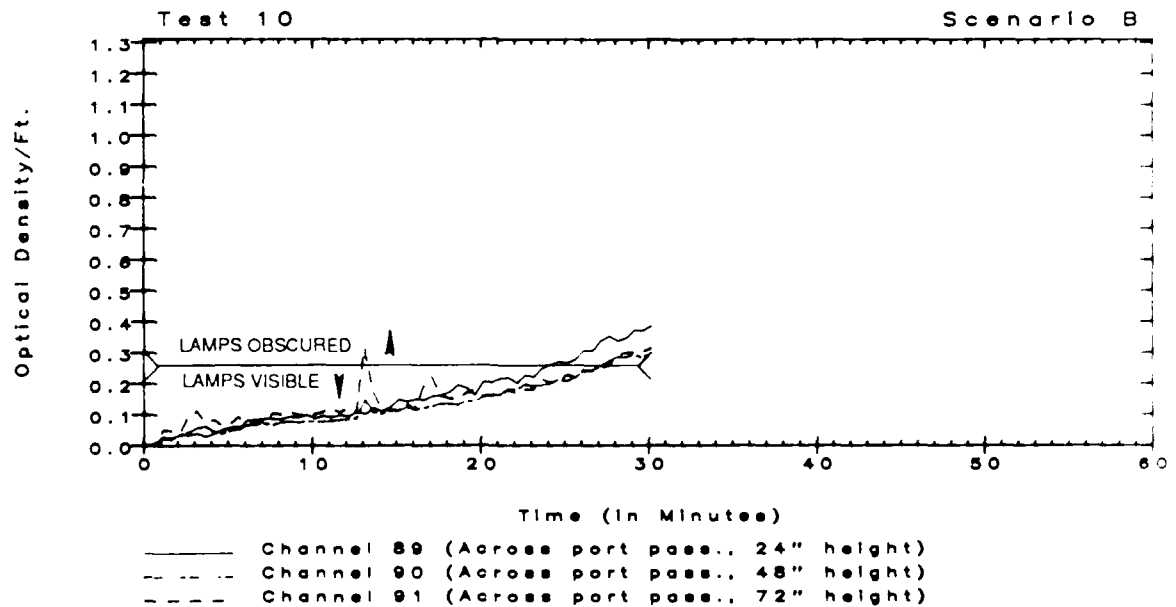
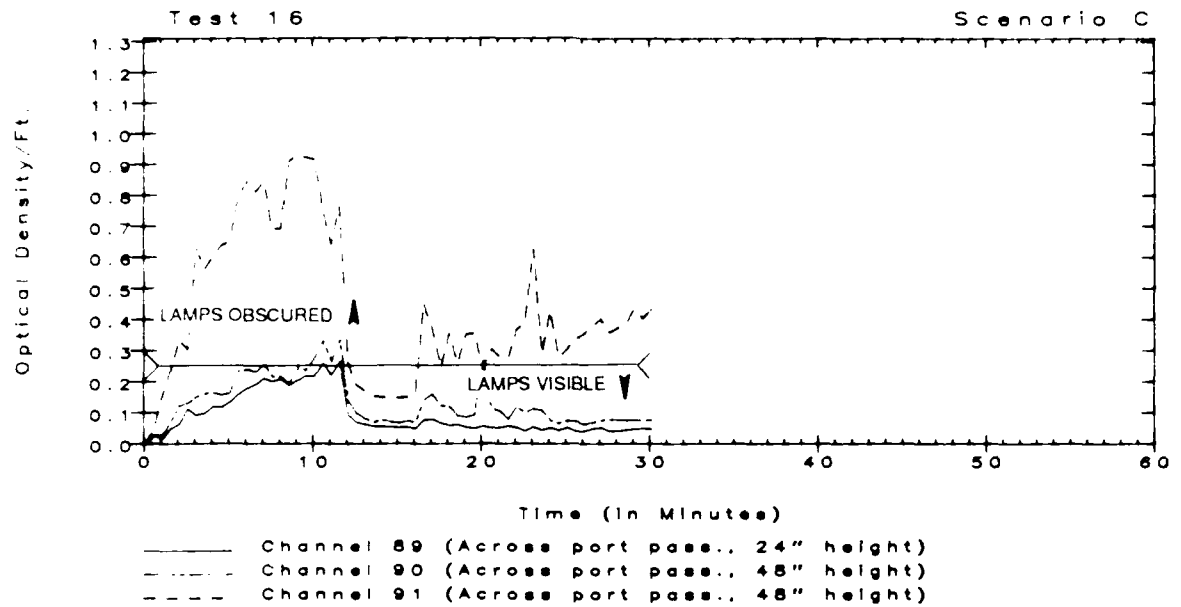


FIGURE 19. Optical Density for Scenarios A and B

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# SF6 TESTS

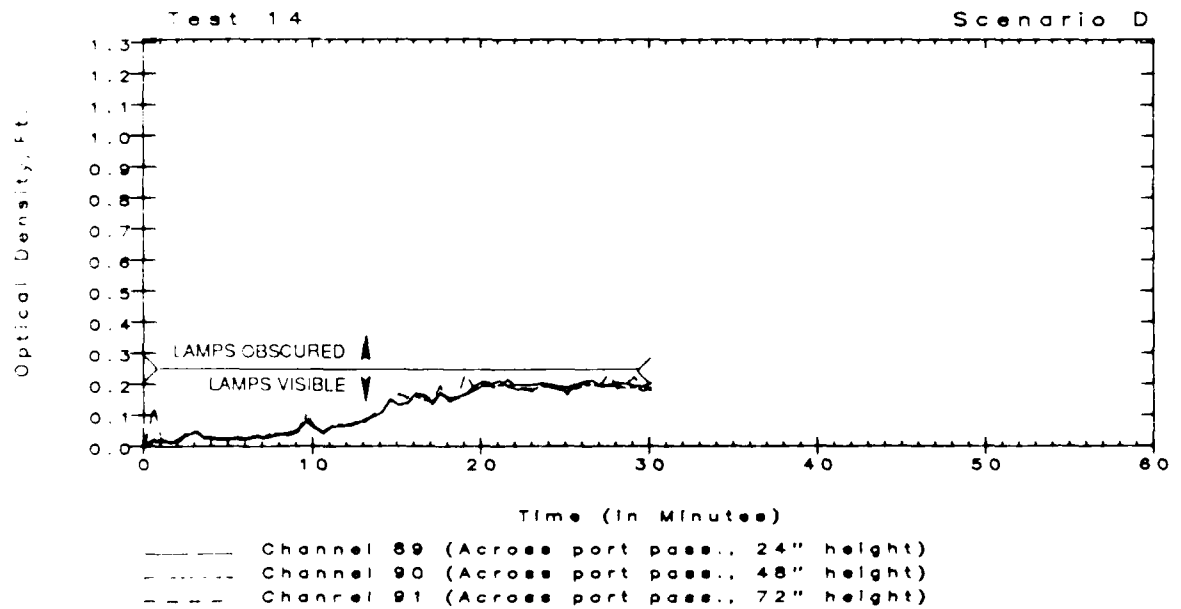


FIGURE 20. Optical Density for Scenarios C and D

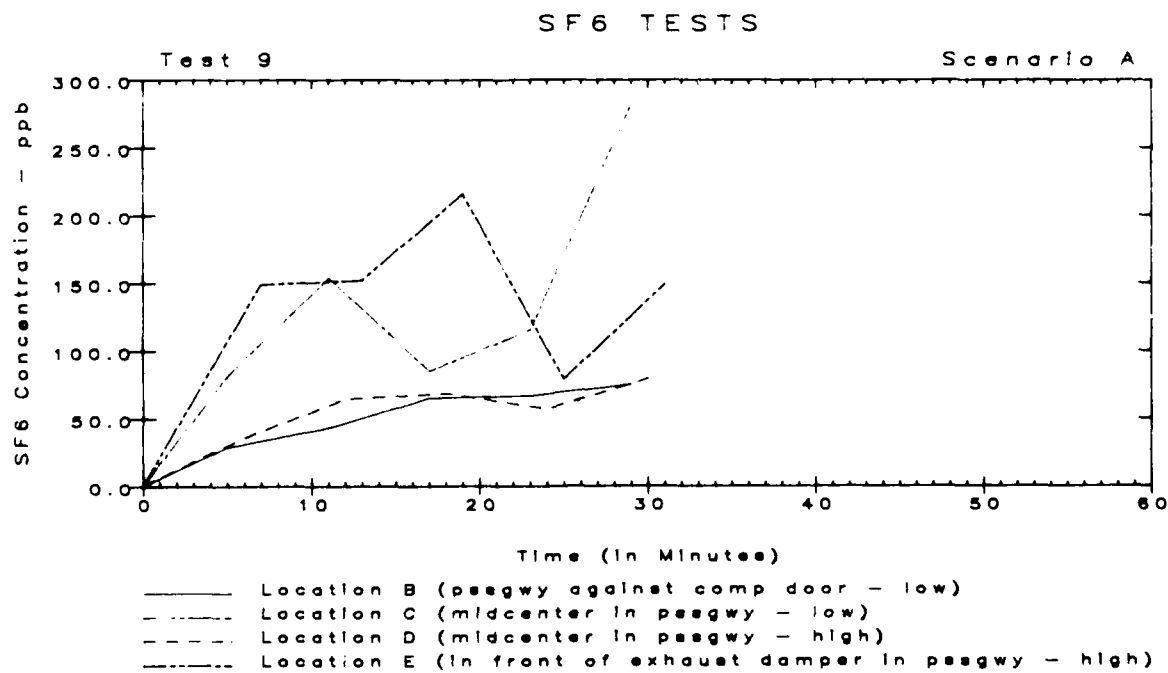
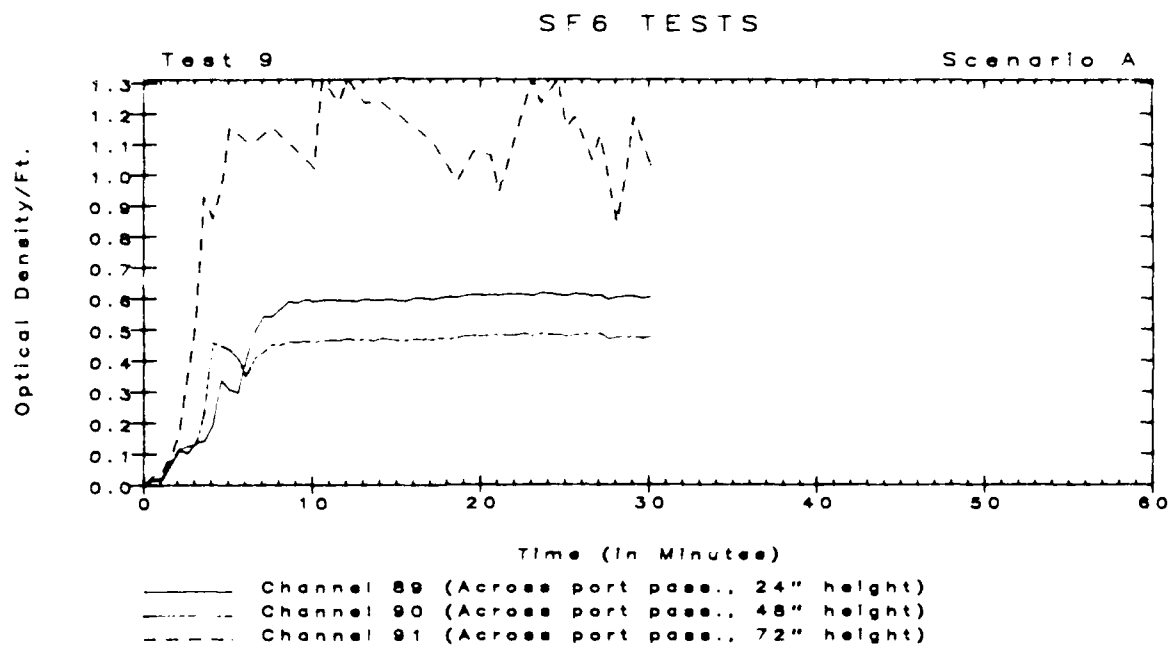


FIGURE 21. Optical Density vs SF6 Patterns for Scenario A

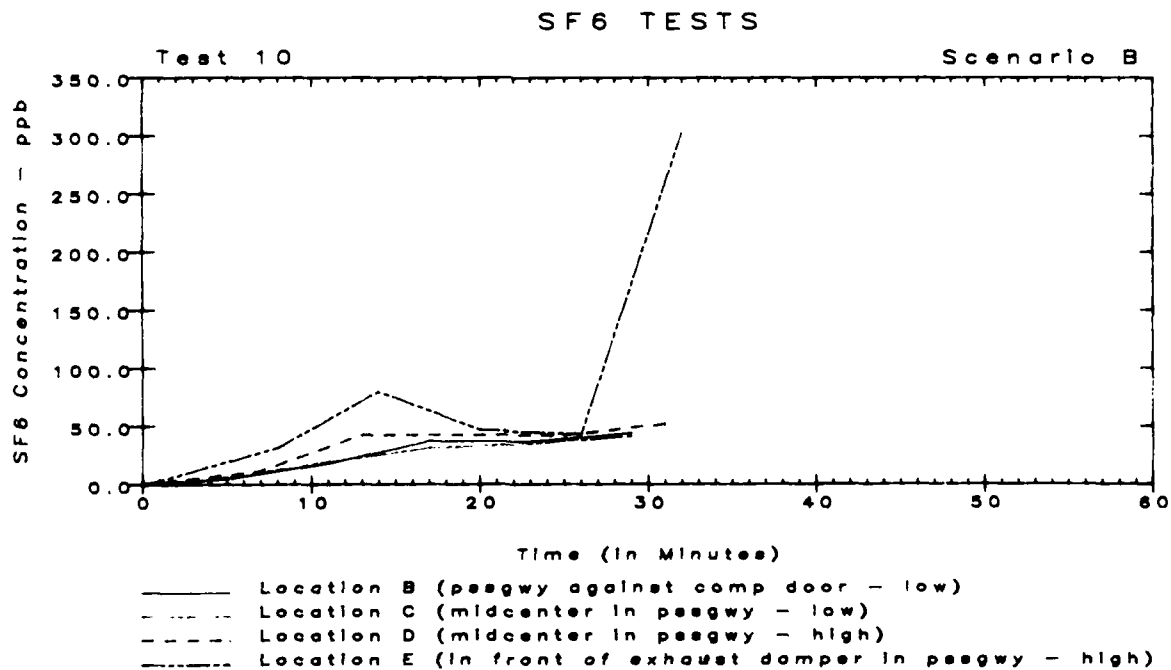
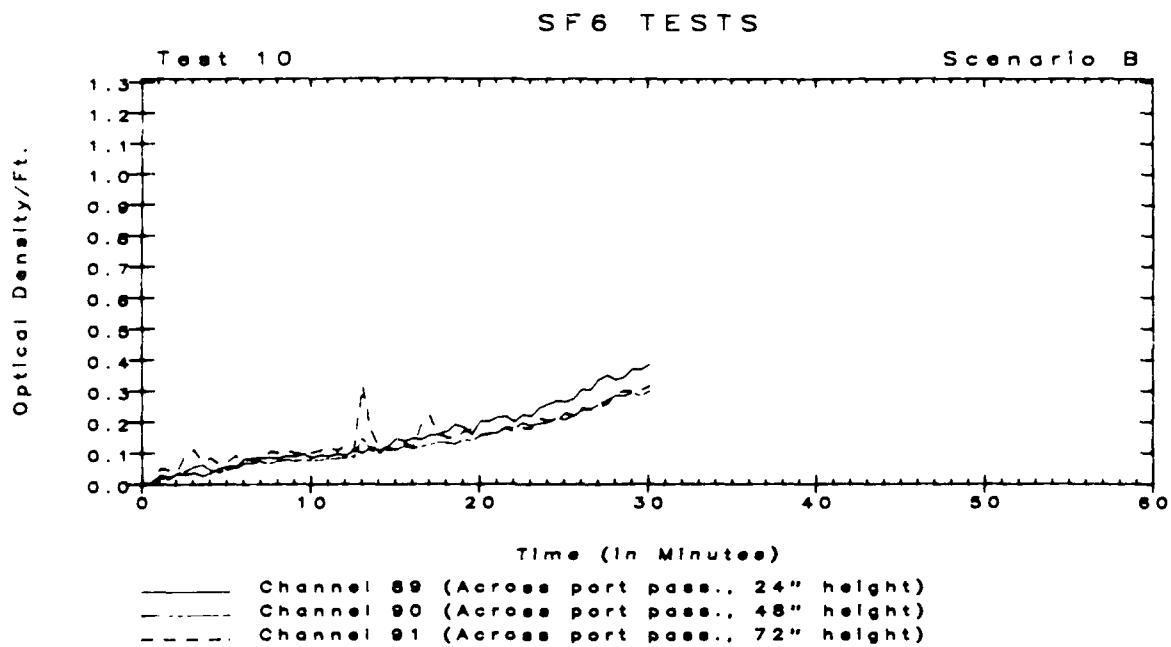


FIGURE 22. Optical Density vs SF6 Patterns for Scenario B

# SF6 TESTS

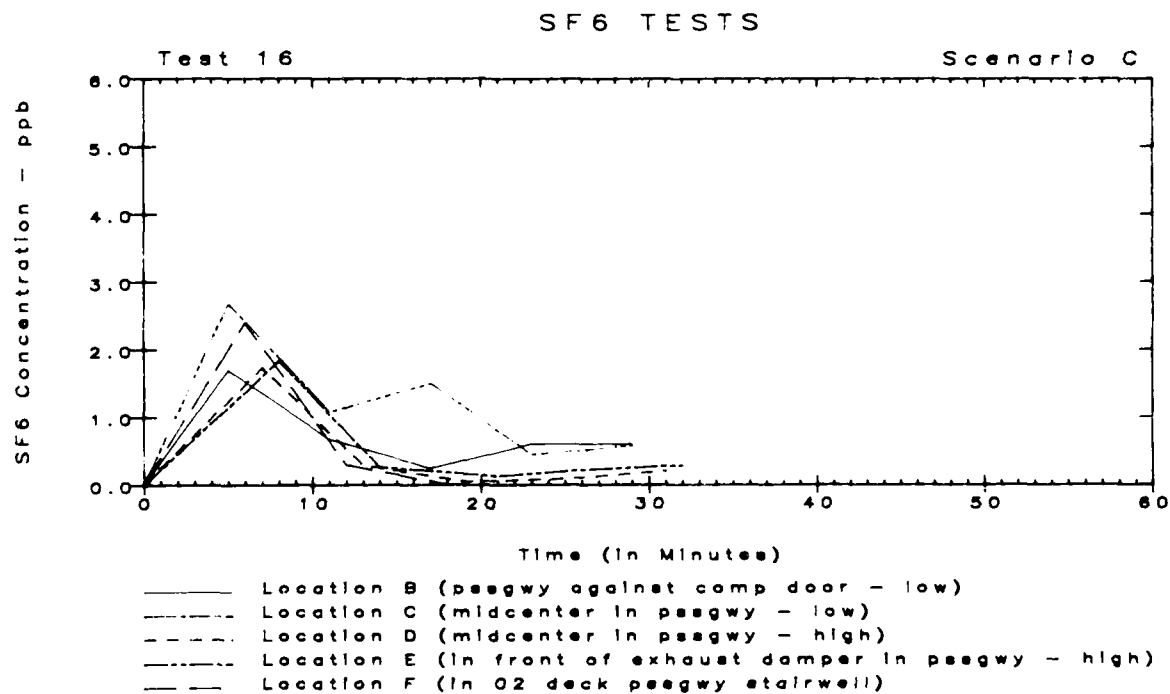
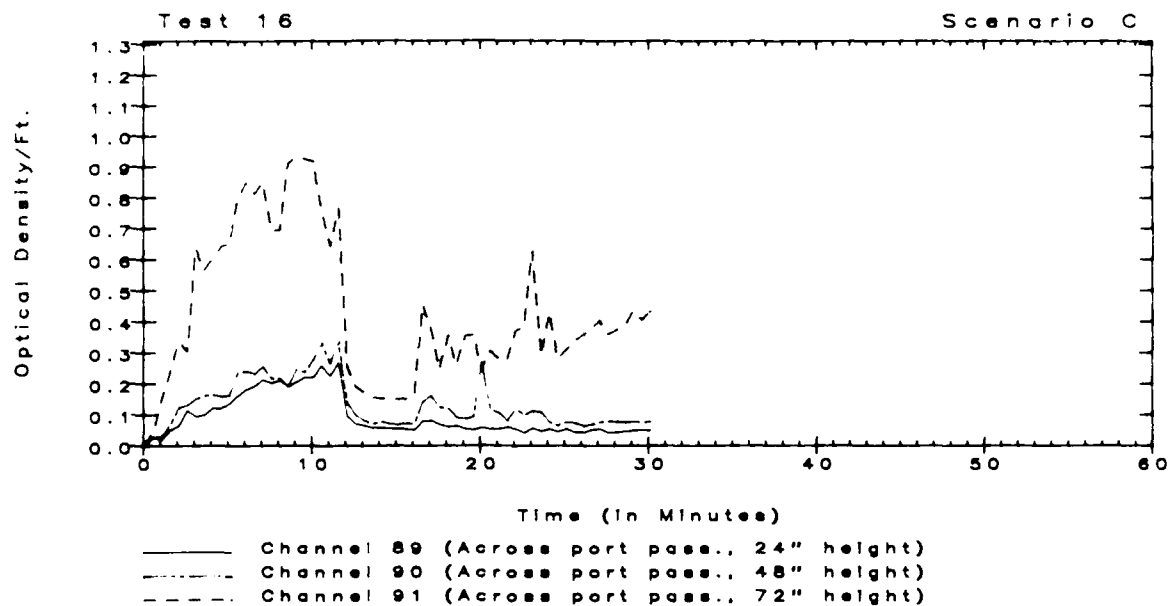
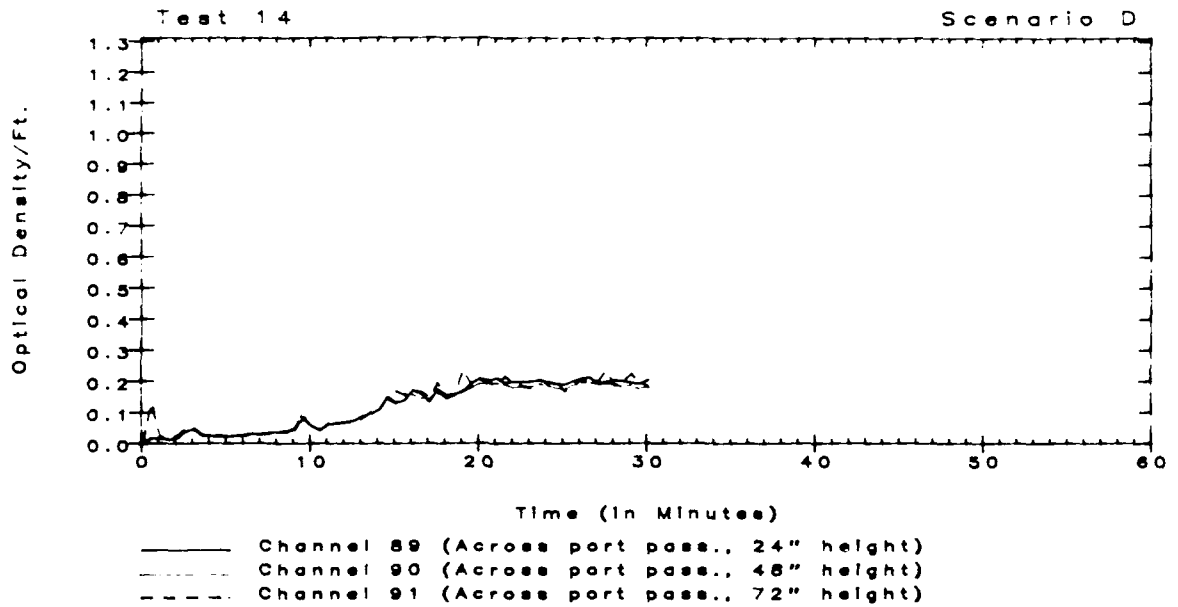


FIGURE 23. Optical Density vs SF6 Patterns for Scenario C

# SF6 TESTS



# SF6 TESTS

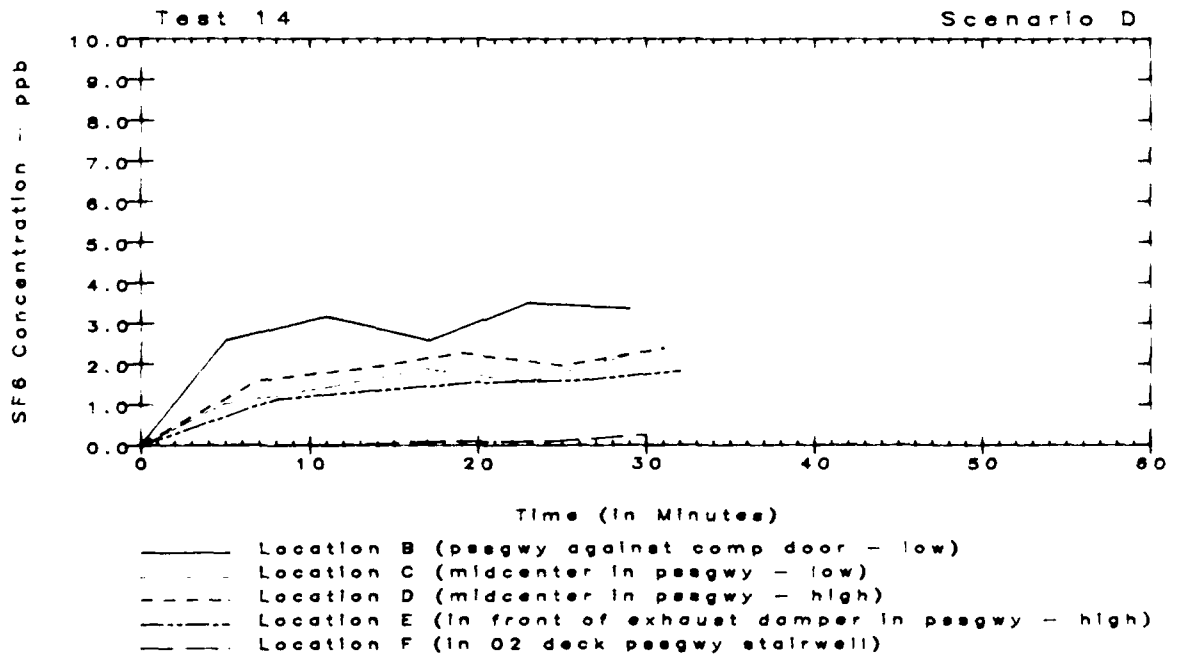


FIGURE 24. Optical Density vs SF6 Patterns for Scenario D

profiles for the same test, we observe that the optical density provides a good qualitative picture of the  $SF_6$  behavior in the hot smoke movement in the test corridor. In plain words, more smoke is indicative of more  $SF_6$ . This similarity of the two patterns is evident even though different  $SF_6$  concentrations and various ventilation/exhaust scenarios were tested. For example, Figures 21, 22, 23 and 24 each represent a different test scenario but the similarity in pattern profiles remains evident even though different test concentrations of  $SF_6$  were used.

The  $SF_6$  profiles which compose the overall pattern of a particular test often changed their concentrations and their relative position in the overall pattern during the three fire tests for each scenario. An example of this is that the highest sampling point (E) in the corridor does not always have the highest  $SF_6$  concentration and the lowest point (C) does not always have the lowest  $SF_6$  concentration. Although the  $SF_6$  profiles often change their relative position in the overall pattern, the pattern which is produced matches the pattern produced by the optical density profiles in the same test. It is correct to say that whenever the optical density indicated high volumes of smoke in the corridor that high concentrations of  $SF_6$  were also reported, and that when the optical density reported low volumes of smoke in the test corridor that low concentrations of  $SF_6$  were reported. The optical density provided a good qualitative picture of the presence of  $SF_6$  in the test corridor but it also indicated that the driving force of each fire varied per scenario and caused havoc with any standard layering effect of  $SF_6$  close to this force.

## 5.0 DISCUSSION OF $SF_6$ RESULTS

Four tests were conducted in the passive mode, four tests were conducted in the dynamic mode and 12 fire tests were conducted. One test of each fan scenario was run in the passive and dynamic modes. Three tests of each scenario were conducted in the fire tests. Findings from each of the three phases will be discussed in the following sections.

### 5.1 Passive Tests

The passive release tests consisted of Tests 1-4. The concentration and flow rates of the  $SF_6$  released were varied to collect data for determining optimum concentration and flow rates for future studies. Consequently, the data will be discussed from the qualitative trends it displays and not the quantitative results.

The most notable feature in all the tests is that for any test all of the sample locations show the same general trend or pattern. For example, in Test 1, Figure 25, the  $SF_6$  concentration rapidly increases at minute 4, drops sharply at minute 6, then steadily rises to minute 40 where it levels out and slowly drops and then levels off to minute 60. In Test 2, Figure 26, the  $SF_6$  concentration rises steeply to minute 20 then peaks between minutes 20 and 30 before quickly dropping after minute 30 to minute 60. Test 3, Figure 27, like Test 1, shows an early peak with a corresponding sharp drop in the first 10 minutes of the test. The  $SF_6$  then rises slowly to about minute 26 where it then rises steeply and peaks at 30 minutes. It then slowly drops off to minute 60. Test 4, Figure 28, like Tests 1 and 3, shows at most locations, the characteristic early peak followed by the corresponding sharp drop. The  $SF_6$  concentration then remains fairly constant throughout the remainder of the tests.

The differences in the four test patterns were caused by the four different fan scenarios, and the four different scenarios can be evaluated by analyzing the test patterns. A good ventilation system will remove  $SF_6$  before it has the chance to build up. Test 4 (fan scenario C) is the only test that illustrates this. At three out of four locations the ventilation system is maintaining a constant low level of  $SF_6$  by 6 minutes into the test. Even at the one location (C) where there is a buildup of  $SF_6$ , the ventilation system is controlling the concentration at about 20 minutes into the test. A poor ventilation system does not control the removal of  $SF_6$  efficiently and permits its buildup. Test 1 (fan scenario B) illustrates this



# SF6 TESTS

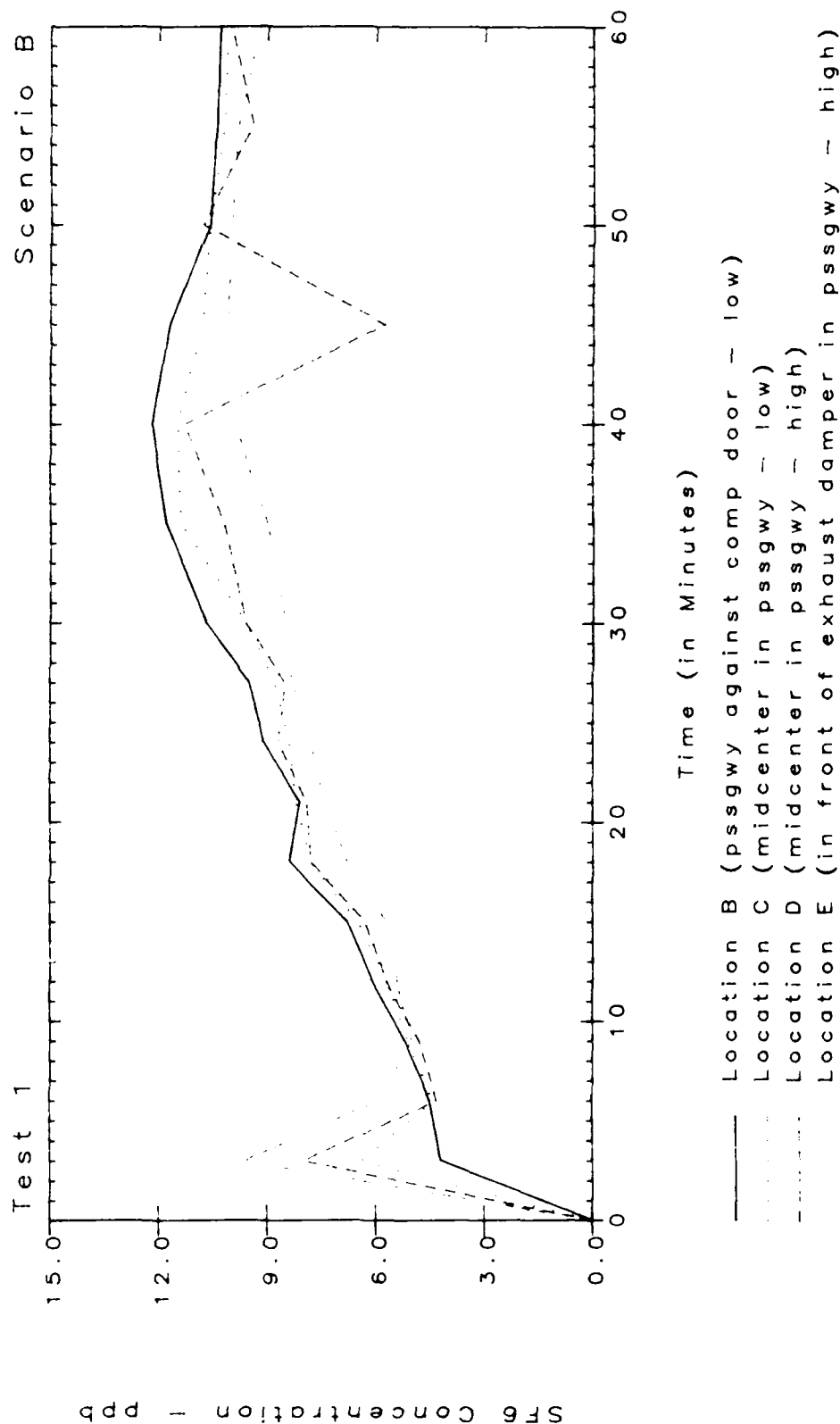


FIGURE 25. SF6 CONCENTRATION, PASSIVE RELEASE -- TEST 1

# SF6 TESTS

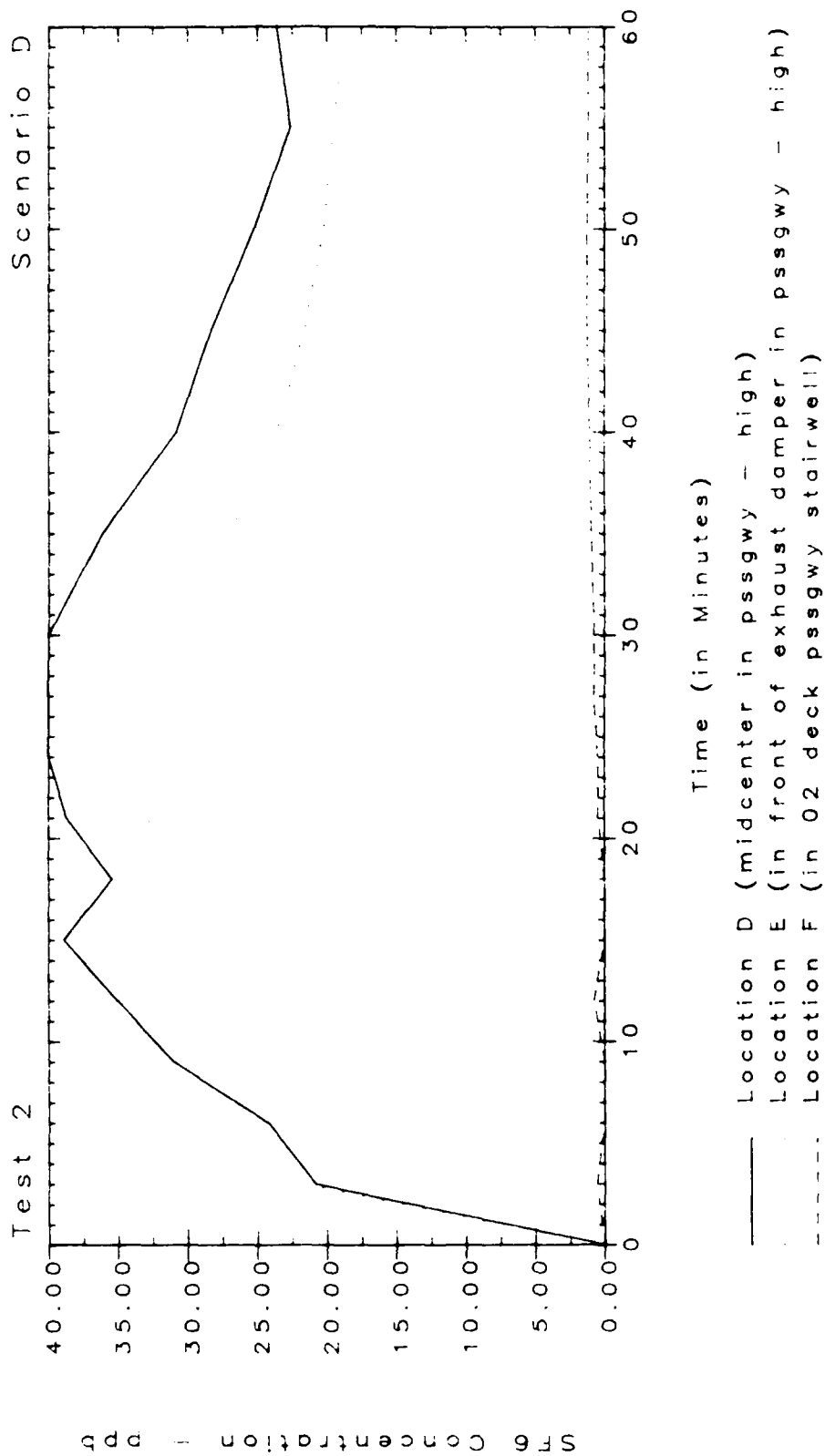


FIGURE 26. SF6 CONCENTRATION, PASSIVE RELEASE -- TEST 2

# SF6 TESTS

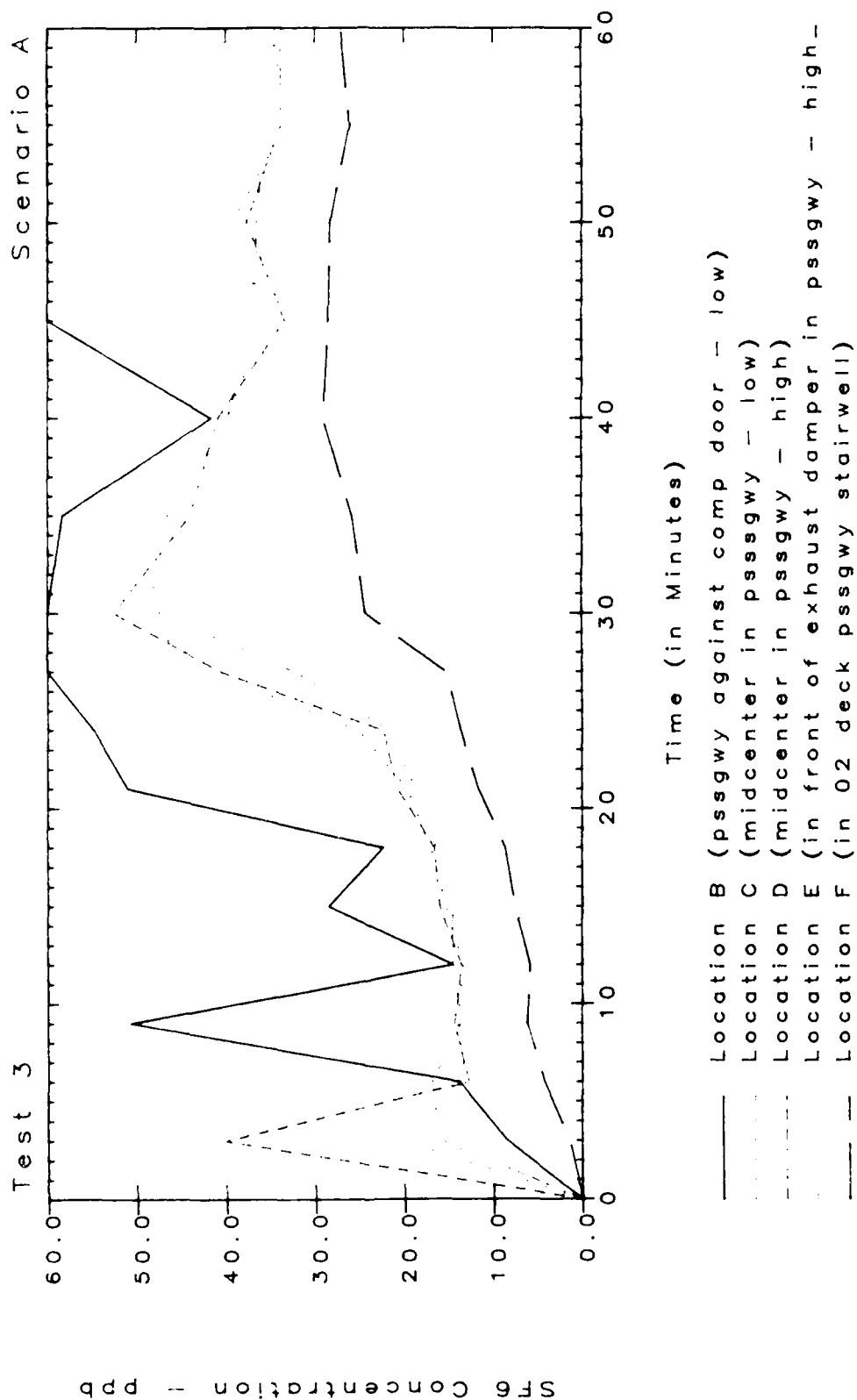


FIGURE 27. SF6 CONCENTRATION, PASSIVE RELEASE -- TEST 3

# SF6 TESTS

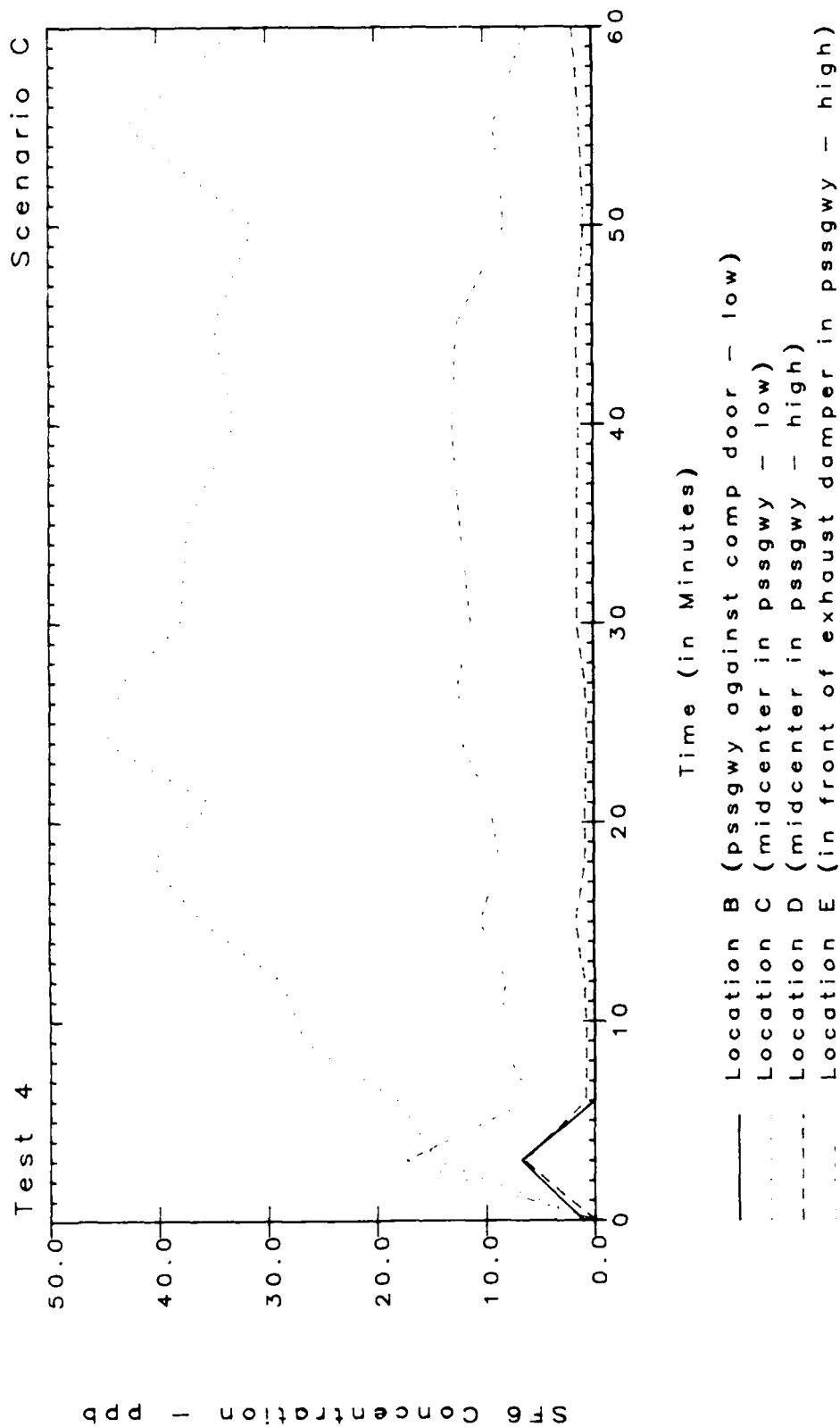


FIGURE 28. SF6 CONCENTRATION, PASSIVE RELEASE -- TEST 4

best. Each sample location in Tests 1, 2 and 3 all show a buildup of  $\text{SF}_6$ . However, Test 1 is the only test to show the buildup continued in the passageway after the  $\text{SF}_6$  was secured at minute 30. The buildup of  $\text{SF}_6$  peaked at about minute 40 and then displayed the slowest decrease of the three tests. Test 2 (fan scenario D) shows  $\text{SF}_6$  buildup until the gas is secured at minute 30. The rapid decrease in  $\text{SF}_6$  concentration after minute 30 indicates the ventilation is effective at removing  $\text{SF}_6$  but cannot remove it at the rate it was being released. Test 3 (fan scenario A) indicates the ventilation is not as effective as fan scenario C or D but appears to be more effective than fan scenario B in that as soon as the  $\text{SF}_6$  is secured the ventilation system begins slowly removing it.

### 5.2 Dynamic Tests

The dynamic release tests consisted of Tests 5-8. The concentration and flow rates of the  $\text{SF}_6$  released were the same for each test and therefore comparisons can be made. The only difference between the four tests was the fan scenario. One of the most notable features common to all four tests is the effect of the forced air fan/blower. As is shown in Figures 29, 30, 31, and 32 (Tests 5, 6, 7 and 8), there is a sharp decrease in the concentration of  $\text{SF}_6$  at each sample location at the time the forced air fan/blower was secured. Similar to the passive tests, the profile of each sample location for a given test is very much like the other profiles for the same test. Since the only difference in the tests is the fan scenario, one can attribute the differences in the patterns to the fan scenario, and the four fan scenarios can be evaluated by studying the test patterns. Since a good ventilation system will remove  $\text{SF}_6$  from the passageway before it has a chance to accumulate, the test showing the smallest concentration of  $\text{SF}_6$  would indicate the most effective ventilation system. Test 8, Figure 32 (fan scenario C) shows the smallest concentration of  $\text{SF}_6$  of the four tests. Test 5, Figure 29 (fan scenario B) shows the greatest accumulation of  $\text{SF}_6$  of the four tests. Like the passive release Test 1, the  $\text{SF}_6$  continues to accumulate in the passageway after the  $\text{SF}_6$  is secured in the fire compartment at minute 30. The  $\text{SF}_6$  doesn't peak until around minute 38. The

# SF6 TESTS

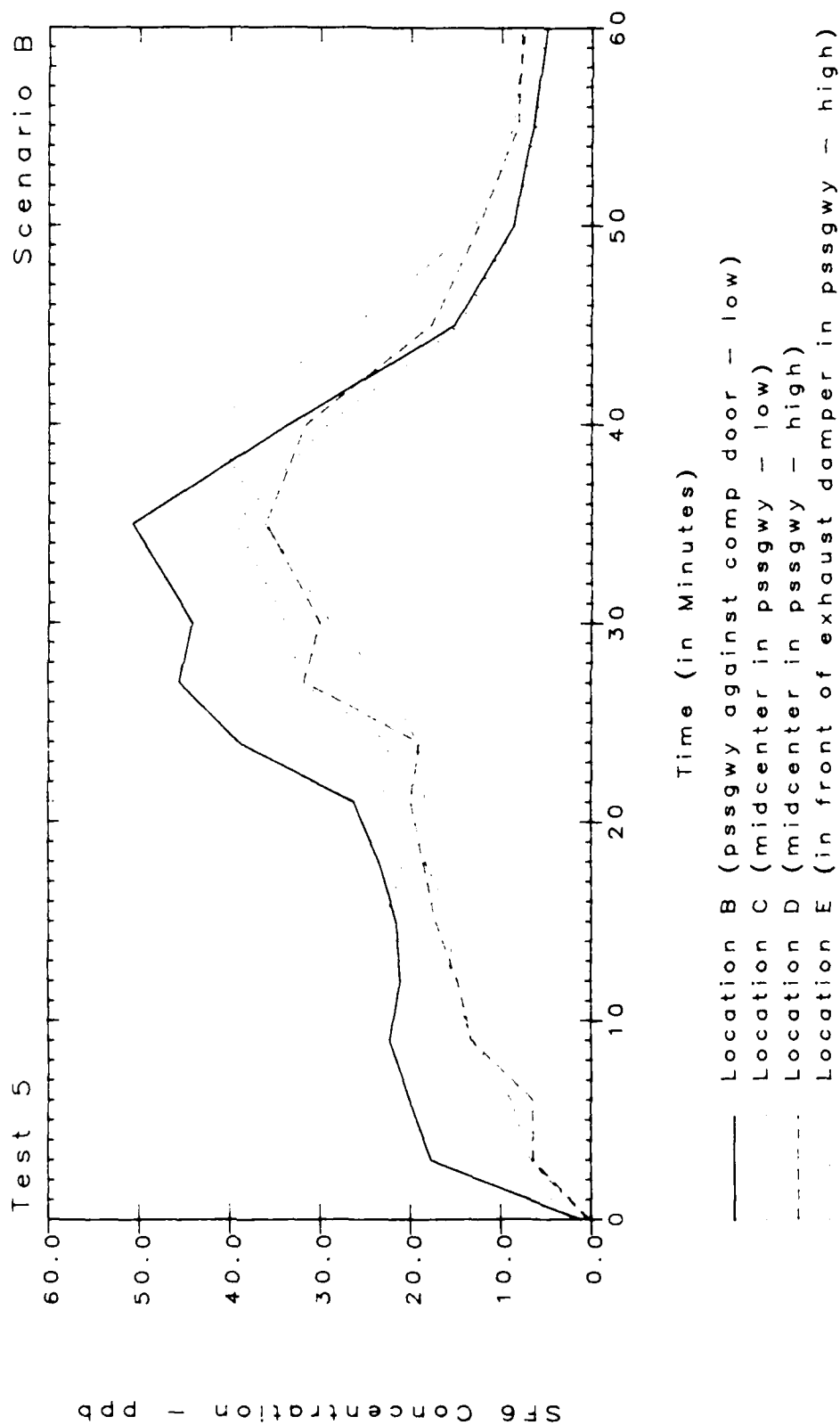


FIGURE 29. SF6 CONCENTRATION, DYNAMIC RELEASE -- TEST 5

# SF6 TESTS

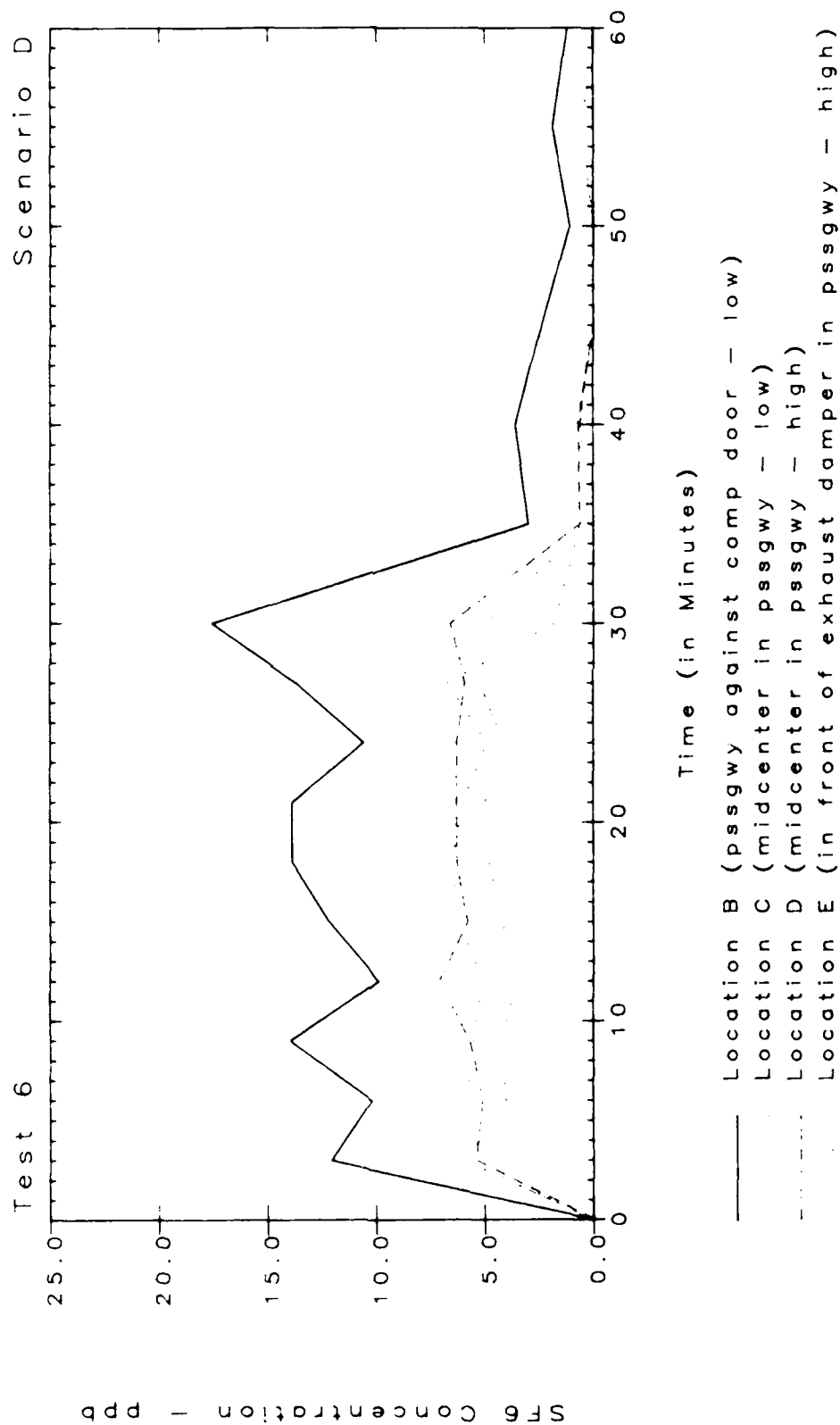


FIGURE 30. SF6 CONCENTRATION, DYNAMIC RELEASE -- TEST 6

# SF6 TESTS

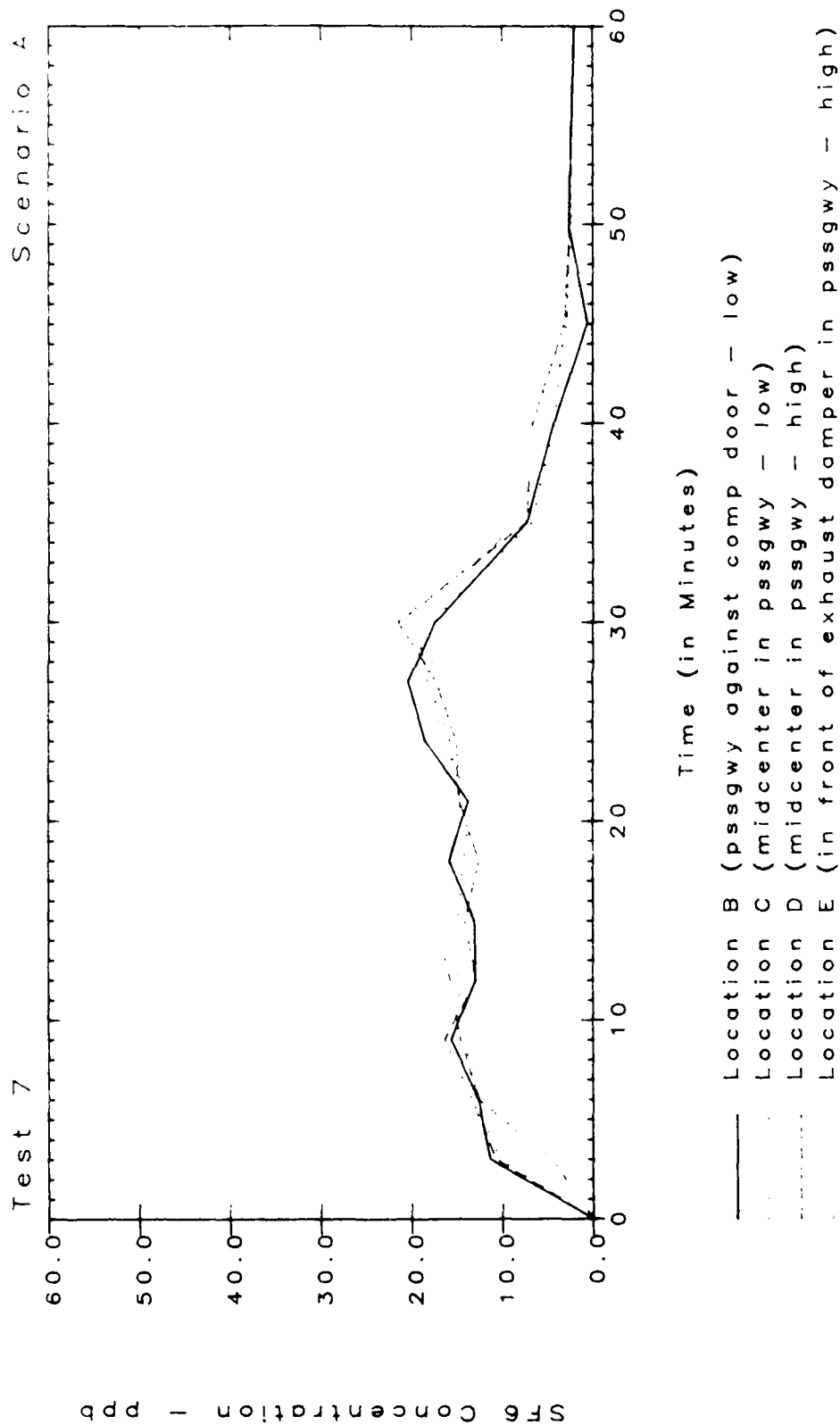


FIGURE 31. SF6 CONCENTRATION, DYNAMIC RELEASE -- TEST 7



# SF6 TESTS

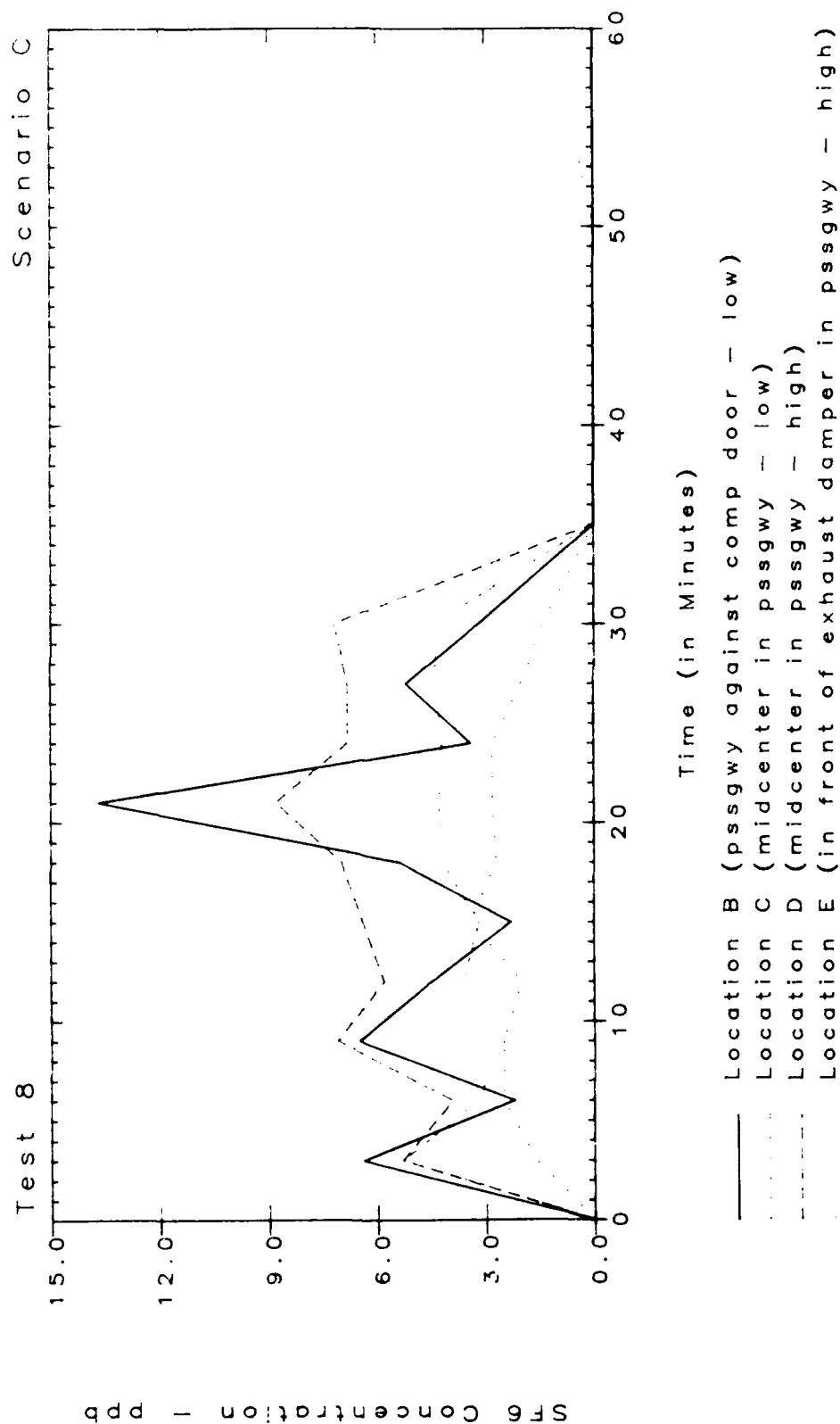


FIGURE 32. SF6 CONCENTRATION, DYNAMIC RELEASE -- TEST 8

ventilation system for Test 6, Figure 36 (fan scenario D), is not quite as effective as the one in Test 8, Figure 32 (fan scenario C), but more effective than the one in Test 7, Figure 31 (fan scenario A).

### 5.3 Fire Tests

Twelve fire tests, three of each fan scenario, were conducted. The same concentration and release rate of  $SF_6$  were used in 8 of these 12 tests. The concentrations detected in these 8 tests were so small that an experimental error in this lower range would significantly alter any results or conclusions. Therefore, we will only analyze quantitative data from tests 9-12. These four tests each had different concentrations and release rates of  $SF_6$ . The detectable levels of  $SF_6$ , however, were large enough to give results that would be unaltered by experimental error. These four tests, like the four tests looked at under the passive and dynamic cases, all showed similar  $SF_6$  patterns at every location in the same test. The patterns differed between the fan scenarios, however. One of the most notable differences between Test 11, Figure 33 (fan scenario C) and Test 12, Figure 34 (fan scenario B), is the  $SF_6$  peak. In Test 11 the peak crests at about 10 minutes and then is rapidly diminished. In Test 12 the peak doesn't diminish until the gas is secured at minute 30. This indicates that despite a large influx of  $SF_6$  into the passageway at the beginning of the fire, fan scenario C was able to remove  $SF_6$  in the passageway quickly, where scenario B just seemed to allow the  $SF_6$  to accumulate.

Test 10, Figure 35 (another fan scenario B) showed a similar pattern to Test 12 but with different concentrations. Test 9, Figure 22 (fan scenario A) showed mixed results and no clear pattern emerges.

### 5.4 Comparison

Despite having graphs that are quite distinct from one another, an analysis of the passive, dynamic and actual fire tests arrive at the same conclusions. That is, for the passive tests, the graphs indicated that fan

# SF6 TESTS

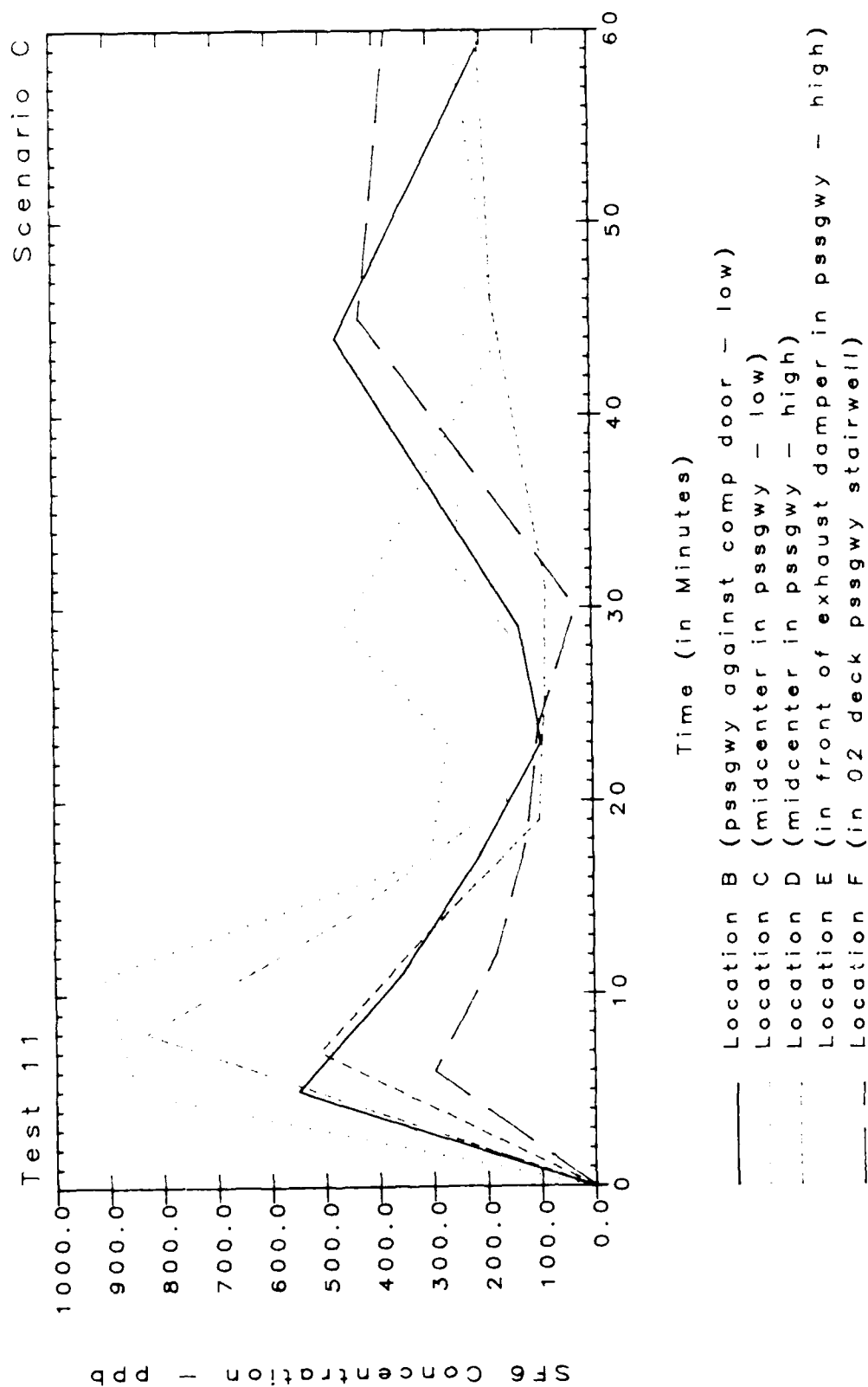


FIGURE 33. SF6 CONCENTRATION, FIRE TEST 11

# SF6 TESTS

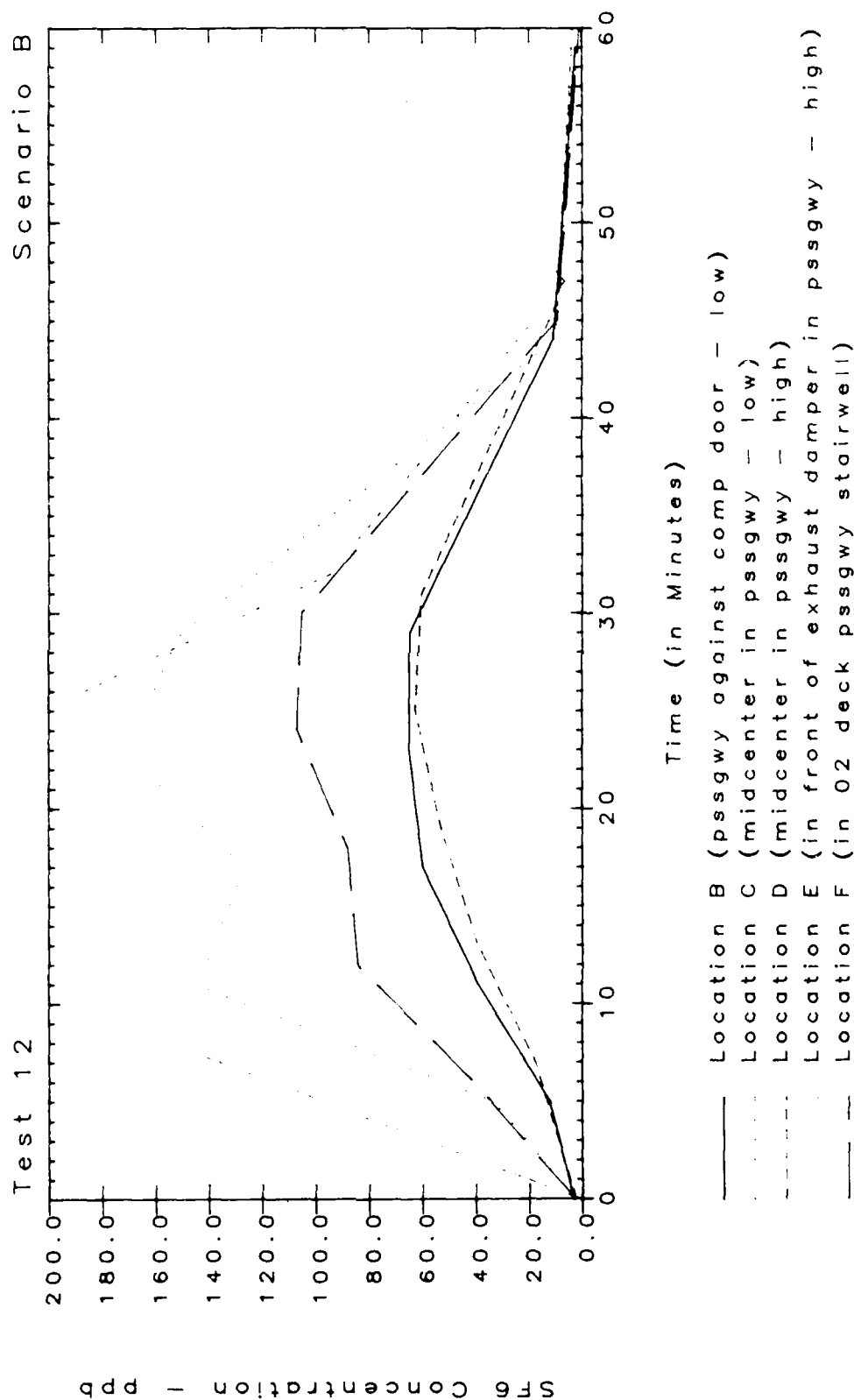


FIGURE 34. SF6 CONCENTRATION, FIRE TEST 12

# SF6 TESTS

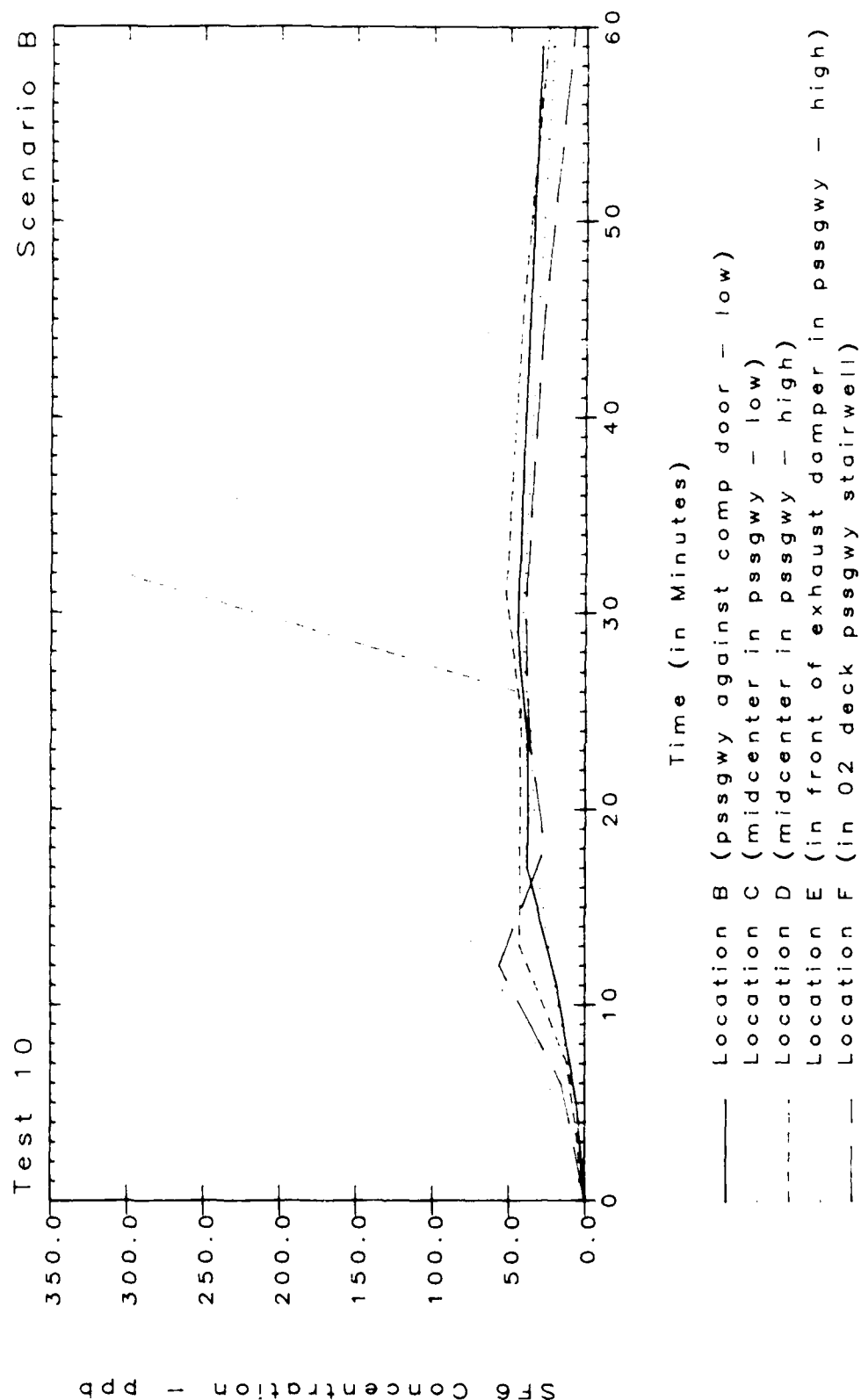


FIGURE 35. SF6 CONCENTRATION, FIRE TEST 10

# SF6 TESTS

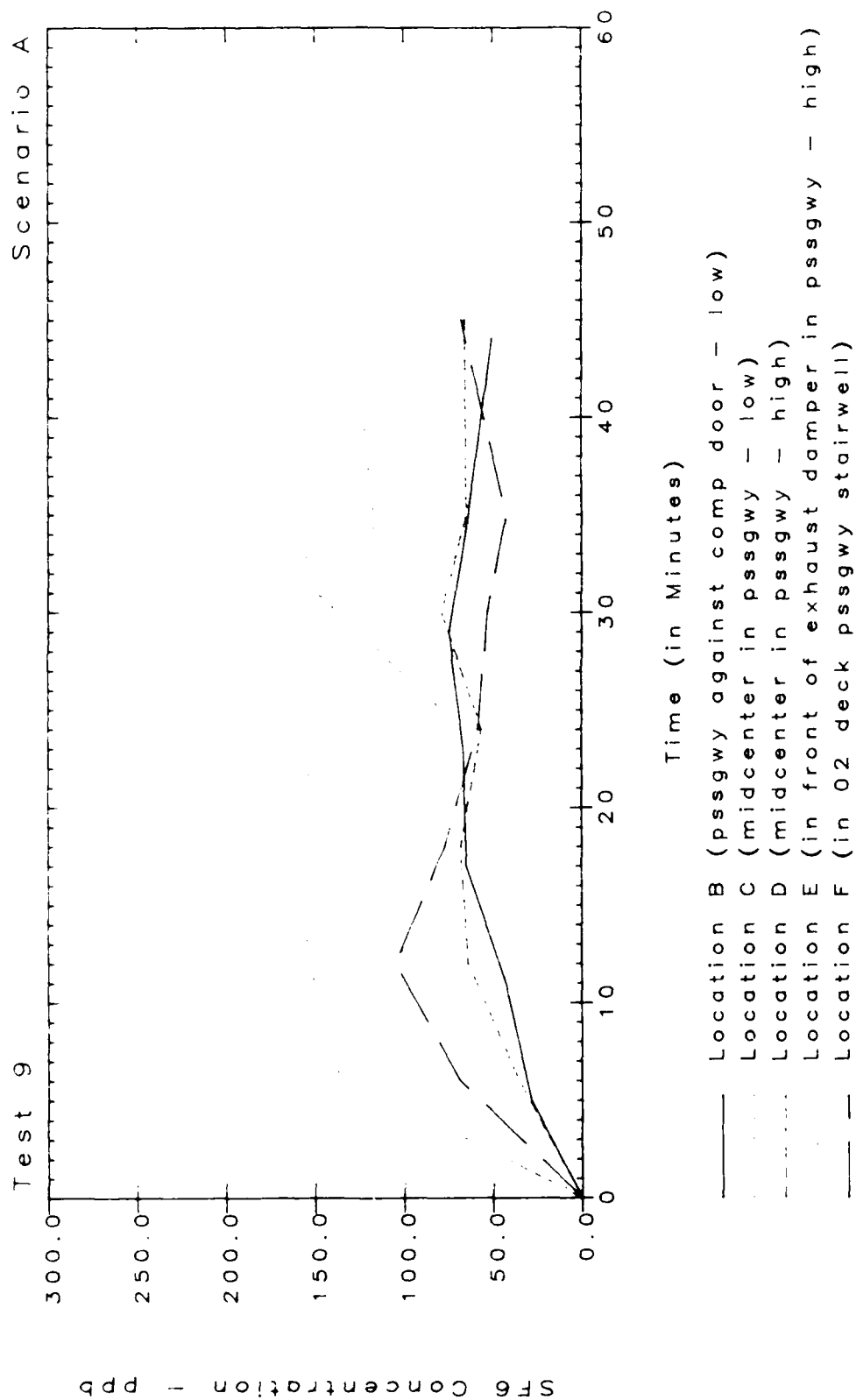


FIGURE 36. SF6 CONCENTRATION, FIRE TEST 9

scenario C was the most effective at removing  $\text{SF}_6$  and fan scenario B most ineffective. Fan scenario D appeared to be more effective than fan scenario B, but not as effect as fan scenario C. The same conclusions were drawn when analyzing data from the dynamic tests and the fire tests.

## 6.0 SUMMARY

The findings discussed in sections 4.1, 4.2, 4.3, 4.4 and 5.4 demonstrate that  $\text{SF}_6$  is a very good tracer gas for smoke movement. However, no quantitative correlation was established between  $\text{SF}_6$  concentration and smoke density.

Section 4.1 (pressure) discussed how  $\text{SF}_6$  follows the tendency of hot smoke to rise in a closed area when the driving force of the fire is removed. In section 4.2 (temperature), it was shown that fire compartment temperatures correlated well with  $\text{SF}_6$  values in the passageway. High temperatures in the fire compartment were observed with high values of  $\text{SF}_6$  in the passageway while low temperatures in the fire compartment were noted with low values of  $\text{SF}_6$  in the passageway. It was also noted that video documentation showed immediate smoke obscuration of the passageway on tests with high temperatures in the test compartment and high values of  $\text{SF}_6$  in the passageway. Likewise, tests with low fire compartment temperatures showed low values of  $\text{SF}_6$  in the passageway and smoke obscuration not occurring until 30 minutes into the test. Smoke obscuration was discussed in section 4.3 (optical density/smoke obscuration). In this section optical density data measured by lasers was compared with video documentation of smoke in the passageway. This comparison showed a high correlation between the time the corridor lamps were obscured in the passageway (as recorded on video) and the optical density values of 0.25 as measured by lasers. In section 4.4 (optical density/ $\text{SF}_6$ ), optical density was compared with  $\text{SF}_6$  concentration. It was shown that when optical density indicated high volumes of smoke in the passageway, there were also high concentrations of  $\text{SF}_6$ . Section 5.4 showed that  $\text{SF}_6$  patterns ranked the ventilation systems in the non-fire tests in the same order of effectiveness for smoke/ $\text{SF}_6$  movement as data indicated in actual fire tests.

All of the data studied indicated that  $SF_6$  can be used to simulate the qualitative movement of smoke. However, there is no evidence that any quantitative correlation exists between  $SF_6$  concentration and the quantity of smoke.

## 7.0 CONCLUSIONS/RECOMMENDATIONS

The test results indicated that  $SF_6$  is a suitable tracer gas for qualitatively determining hot smoke movement onboard vessels.

The four fan scenarios created two basic pressure conditions inside the test citadel. Within both pressure conditions the  $SF_6$  behaved similar to hot smoke. It was discharged from the fire compartment into the passageways. From there, it rose from the release deck to the upper deck through an open stairwell but it did not descend through the open stairwell to the deck below the test deck.

A correlation existed between compartment temperatures and  $SF_6$  concentrations in the test corridor. That is, high compartment temperatures resulted in high  $SF_6$  concentration in the test corridor while low temperatures in the test compartment resulted in low concentrations of  $SF_6$  in the test corridor.

The movement of  $SF_6$  can be correlated to that of hot smoke by comparing the test times when  $SF_6$  appeared in the test corridor to the test times when smoke was observed in the video recordings of the test corridor.

A quantitative correlation between smoke density profiles and  $SF_6$  profiles could not be determined, but the results did indicate that the  $SF_6$  patterns followed the optical density patterns at corresponding times in the test corridor.



SF<sub>6</sub> can be used to evaluate ventilation systems relative to one another without conducting destructive fire tests. The passive SF<sub>6</sub> release mode, the dynamic release mode, and the fire tests all ranked the four fan scenarios in the same order of effectiveness for the movement of SF<sub>6</sub>/smoke.

The dynamic release mode creates a driving force which thoroughly mixes the SF<sub>6</sub> in the test environment, while the passive release mode allows the SF<sub>6</sub> to follow the natural distribution attributed to the influence of air movements present in the test environment.

The SF<sub>6</sub> profiles occurring from the passive release mode are maintained long after the SF<sub>6</sub> is no longer being released while the SF<sub>6</sub> profiles produced by the dynamic release drop off and seek the normal existing air flow movements.

A high concentration release rate of SF<sub>6</sub> rather than a low concentration release of SF<sub>6</sub> will produce test data which is less susceptible to marginal error.

Further testing is recommended to determine whether the passive or dynamic release mode is a better predictor of actual smoke movement. This testing should be conducted with a standard release concentration of SF<sub>6</sub>.

## REFERENCES

1. Carey, Richard; Finger, Stanley; Keith, Virgil; Mondor, Robert; Porricelli, J.D. Fire-induced Smoke Removal Using A Modified Shipboard Collective Protection System. David W. Taylor Naval Ship Research and Development Center, July 1982.
2. Klote, John H. and Zile, Richard H.. Smoke Movement and Smoke Control on Merchant Shios, National Bureau of Standards. NBSIR 81-2433, December 1981.
3. Helgeson, W.C. and Schultz, H.E.. A Method For Evaluating Smoke Control On Ships Using SF<sub>6</sub> Tracer Gas. Department of Transportation and U.S. Coast Guard, December 1983.
4. Klote, John H. and Fothergill, Jr., John W., Design of Smoke Control Systems for Buildings, U. S. Veterans Administration, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. and U.S. Department of Commerce, September, 1983.
5. National Fire Protection Association. Fire Protection Handbook, Fourteenth Edition, 1976.

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